Effects of Fire on Fuels

A State-of-Knowledge Review
National Fire Effects Workshop
Denver, Colorado
April 10-14, 1978

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United States
Department of
Agriculture
Forest Service

General Technical Report WO-13

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A State-of-Knowledge Review

Prepared for the Forest Service National Fire Effects Workshop
Denver, Colo.
April 10–14, 1978

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U.S. Department of Agriculture
Forest Service
General Technical Report WO–13

September 1979

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

PREFACE

Recent changes in Forest Service fire management policy make it clear that resource managers today need a great deal more information on the physical, biological, and ecological effects of fire. They will need information on fire behavior and fire effects as a basis for analyzing the benefits, damages, and values of various fire management alternatives. Managers must be able to place a value on all resources if they are going to incorporate fire and its effects into land management plans. The Forest Service is committed to the concept that fire management planning has to be a fundamental part of all our planning.

Recent laws and regulations also give additional guidance for the Forest Service to use in developing land management plans for each unit of the National Forest System. These plans must coordinate outdoor recreation, range, timber, watershed, wildlife and fish, and wilderness resoures. Interdisciplinary planning is vital, and research must cover the same universe as our planning—therefore interdisciplinary research is a must.

The effects of fire have been studied since the beginning of organized Forest Service Research, but the results are scattered over a wide range of outlets. In addition, research is conducted on the effects of fire under several appropriation line items, and in some instances lacks the interdisciplinary approach needed to make the results as useful as possible to land managers.

The National Fire Effects Workshop was held April 10 through 14, 1978, as a first step in responding to the most recent changes in policies, laws, regulations, and initiatives. One of the major Workshop objectives was to prepare a report indicating the current state–of–knowledge about effects of fire on various resources. These reports formed the basis for pinpointing knowledge gaps. Using this information and input from land managers, priorities for research needed on the effects of fire were established.

Six work groups were established to prepare the state–of–knowledge reports on the following projects: soil, water, air, flora, fauna, and fuels. Work group members were mainly research scientists and employees in other disciplines from the Forest Service, but employees of Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Bureau of Indian Affairs also participated.

We hope these state–of–knowledge reports will prove useful to researchers and research planners as well as land and fire management planners. Each report will be published as an individual document. A separate bibliography also will be included in this series in an effort to provide a source document for most of the literature dealing with the effects of fire.

CONTENTS

INTRODUCTION

This report summarizes the current state-of-knowledge concerning the direct and indirect effects of fire on fuels. Both wildfires and prescribed fires are considered. More specifically, the report:

1) Summarizes pertinent information on the effect of fire on fuels (biomass);
2) Describes major gaps in knowledge concerning these effects;
3) Recommends research to fill these gaps.

Fuels contain energy, stored over extended periods through photosynthetic processes, that is released rapidly, occasionally explosively, in combustion. By definition, fuels consist of both living and dead plant materials.

The amount of energy potentially available is directly proportional to mass or fuel load, but there are other properties of fuels that must be considered if the fire potential on a site is to be adequately assessed. These properties affect not only the amount of heat and its form, but also the rate of heat release.

The basic element of fuel is the fuel particle. Heat value is determined by particle chemistry: The contents of terpines, crude fats, noncombustible minerals such as silica, and a group of minerals that chemically inhibit combustion. The moisture content of the fuel particle is especially important, as is the ratio of its surface area to its volume (fineness).

Fuel elements are combined into a fuel bed. The fuel bed, in turn, has characteristics that also affect flammability. The distribution of the sizes of fuel elements and the ratio of live–to–dead components are very influential. But there are other properties that must be accounted for. Flammability is particularly sensitive to compactness and continuity, both horizontal and vertical.

Forest and rangeland fuel conditions are not static. In the long term (10 to 100 years), changes in species composition affect fineness and continuity. Loadings, particle densities, and compactness vary in the medium term (1 to 10 years). Seasonal trends occur in particle heat values, ratio of live-to-dead fuel components, and the moisture contents of live plants and the larger dead fuel elements.

Next, one must consider three weather time scales: the planetary (wet or dry "spells" or cycles—10 days to months), synoptic (frequency of high and low pressure systems, storms, etc.—1 to 10 days), and diurnal (1 to 24 hours).

The rating of fire danger is the most established method of assessing fuel flammability. In the National Fire Danger Rating System, some capability exists to account for all of these factors except those that occur on the diurnal time scale.

Stylized fuel models can be used to account for long- and medium-term changes in fuels. These models specify loadings of two live and four dead fuel classes. Surface-to-volume ratios, heat values, and the fuel bed compactness are also supplied. The fuels are assumed to be continuous and to occur in a single stratum.

For the seasonal and two longest weather time scales, the National Fire Danger Rating System tracks the moisture contents of the six fuel components and the live–to–dead ratio of the finer material (grasses and/or forbs and dead material less than ¼ inch in diameter).

It is important before we continue with a discussion of fuels to point out the obvious relationships of fuels to the soil, topography, climate, and biota of a given site, as well as the impacts caused by man or other agents. How much of what kind of fuel accumulates on a site is dependent on the time a given abiotic and biotic complex has had to produce and decompose the material. The biotic complex in turn is affected by the abiotic factors. Both are affected by the incidental impacts of other agents in the system. Man, wind, fire, insects, and disease may be considered as part of the system or as outside influences grossly altering the direction of biological progression through such occurrences as clearcutting, catastrophic fire or wind damage, or insect and disease epidemics. On the other hand,

light thinnings, frequent light fires, occasional wind damage, or endemic insect and disease situations might be considered as part of normal vegetative progression. Fuel or biomass production, decomposition, and accumulation are modified by all these influences, whether epidemic or endemic, catastrophic or moderate.

In discussing our knowledge—and lack of knowledge—concerning fuels, we must also consider that we are also short on models of how fuels affect fire as well as how fires affect fuels. Rothermel's (1972) fire spread model is the most versatile, yet it represents only fire spread in uniform, homogeneous fuels. We lack models for fire behavior in nonuniform, heterogeneous fuel beds.

Because fire affects both the biotic and abiotic characteristics of wildlands, it therefore affects the potential commodity and amenity values of those lands. Whether those effects are beneficial or detrimental depends on the management objectives and the size and intensity of the fire. Fire size and intensity are affected by fuel and meteorological and slope characteristics, as well as suppression capability. We have no control over weather or slope, but we can provide appropriate suppression capability, and we can use prescribed fire to assure meeting management objectives. To some degree, we can manipulate fuels.

An appropriate level of fuels knowledge is required to assure that fire management activities will meet land management objectives. The difficult question is "What level of fuels knowledge is needed?" The knowledge level should be determined by the sensitivity of the management decision to the accuracy of the fuel information. A low level of fuels accuracy such as that provided by the 20 Fire Danger Rating models may be adequate for planning fire suppression capabilities to meet fire size objectives. Establishing prescriptions to meet silvicultural or wildlife habitat needs may well require much more complete knowledge of fuel characteristics. Beyond fire danger rating, considerable sophistication is possible for predicting fire behavior and fire effects. Dynamic fuel models such as those developed for southern California chaparral, which trace all of the fuel particle and fuel bed properties, are examples (Rothermel and Philpot 1973). Albini and Brown (1978) incorporated dynamic features that account for aging (settling, fines dropping, etc.) in their slash hazard appraisal system.

Diurnal trends and site-to-site variation of fuel moisture due to aspect, elevation, slope, and sheltering by overstory are required for fire behavior prediction. Such site-specific data are beyond that required for fire danger rating.

TERMINOLOGY

The terminology presented here is intended only as a brief summary concerning terms used in this report. Most units are presented in the English system regardless of the units given in the source papers. A table of conversions is given at the end of the text.

1. Fuel management—manipulation of vegetation and organic matter (fuels) to enhance the role of fire management and other groups in meeting land management objectives. Fuel management should begin with manipulation of the vegetation. Fuel management may include:
   a. modifying vegetation so it is less flammable, especially during the fire season;
   b. reducing the amount of fuel available to burn;
   c. reducing the flammability of fuels;
   d. developing vegetative and fuel mosaics to isolate hazardous areas and reduce firespread.

   Of three things affecting fire behavior—weather, topography, and fuel—fuel is the only one over which we have any degree of control.
2. Fuel characterization—physical, chemical, and distributional properties of fuels in a vegetation type. An infinite arrangement of fuels can exist but discrete strata are recognized and may be affected by fire. These strata are:
   a. duff and litter (the L, F, and H layers) (See Lutz and Chandler 1946, p. 225, for definition.);
   b. grass and forbs (live and dead, generally less than 4 feet high);
   c. shrubs (live and dead, generally within 6 feet of the ground, but may be taller);
   d. dead and down woody material (within 6 feet of ground), in at least four size classes:
      1. 0 to 0.25 inch
      2. 0.25 to 1.0 inch
      3. 1.00 to 3 inches
      4. greater than 3 inches
   e. regeneration (live and dead, standing);
   f. timber (live and dead, standing).
3. Fuel inventory—measurement of fuels, using basic understanding of fuel characterization and fire modeling to govern procedures.
4. Fuel appraisal—combining the fuel characterization and inventory to provide an estimate of fuel within a stand and potential fire behavior.
5. Fuel classification—fuels may be classified in many ways, each contributing to our description of them.
   a. Whether or not the fuel burns (Byram 1959).
      1. available fuel—quantity that actually burns in a forest fire;
      2. total fuel—quantity of fuel on site; may include all live fuels;
      3. residual fuel—that left after a fire.
   b. Position (Davis 1959)
      1. aerial fuel—that fuel more than 6 feet above mineral soil surface;
      2. ground fuel—that fuel lying on or within 6 feet of mineral soil surface;
      3. ladder fuels—those fuels which tend to be continuous between the ground fuels and tree crowns, forming a "ladder" by which fire may spread into the tree crowns;
      4. another position classification includes:

         aerial—more than 6 feet above mineral soil;

         surface—less than 6 feet above mineral soil and above the decayed organic matter of the forest floor; it includes low brush surface litter, and most slash;

         ground—organic matter below the loose surface litter; it includes humus, roots, peat, and muck.

c. Categories, as used in National Fire Danger Rating System (NFDRS).
   1. live—grouped as herbaceous or woody;
   2. dead—grouped by size class as 1, 10, 100, 1,000 hour time lag (T.L.) classes; often separated into sound and rotten.

d. Time lag constant—the time for a material to drop about 63 percent ($1 - 1/e$ where e is the base of natural logarithms) of the difference between its moisture content at the beginning of the time period and the new equilibrium moisture conditions to which it is exposed. For example, a fuel particle beginning at 20 percent moisture content and exposed to 10 percent equilibrium conditions would drop to $20 - 0.63 (20 - 10) = 20 - 6.3 = 13.7$ percent moisture content in one time lag period. If the period is 1 hour, the fuel has a 1 hr. T.L.

e. Size classification (as in NFDRS) and general usage

	Time lag class			
	1 hr	*10 hr*	*100 hr*	*> 100 or 1,000 hr*
Time lag class interval	0–2	2–20	20–200	> 200 or 200–2,000
Equivalent fuel dimensions:				
Roundwood	< ¼″	¼ to 1″	> 1 to 3″	> 3″
Litter and/or duff	Surface	Surface to ¾″	> ¾ to 4″	

6. Fuel model—a simulated fuel complex for which all the fuel descriptors required for the solution of the mathematical fire spread model have been specified:
   a. stylized—parameters set at given levels, such as those in National Fire Danger Rating System (Deeming et al. 1978) or Albini (1976);
   b. static—parameters defined for only a short period of time, say a few months or years;
   c. dynamic—fuel parameters defined or predicted for several years.
7. Mathematical fire spread model—one of many mathematical systems used to compute fire spread and other fire characteristics; in forest fire work, we generally use Rothermel's (1972) model.
8. Fuel moisture content—the amount of moisture in a fuel generally calculated as a percent of ovendry weight (M.C. %) as follows:

$$\text{M.C. \%} = \frac{(\text{Field weight}) - (\text{Ovendry weight}) \times 100}{\text{Ovendry weight}}$$

Fuel moisture sticks are calibrated to read directly in percent moisture content. Moisture contents of other fuels can be measured by collecting and placing in a vapor-tight container, obtaining field weight, ovendrying at 220° F (105° C) to a constant weight (generally 1 to 4 days depending on size), and reweighing. If weight of container is included in weighings, it must be subtracted before doing calculations.
9. Equilibrium moisture content—the moisture content a fuel particle would attain if exposed for a long time to a constant temperature and humidity.
10. Critical properties of fuel (from Brown et al. 1977)
    a. moisture content
    b. particle size
       1. surface area to volume
       2. relates to heat and moisture exchange
    c. quantity
    d. compactness
    e. continuity

EFFECTS OF FIRE ON FUELS

The information on the following pages is a brief encapsulation of what has been done on fuels or biomass. We have attempted to cover most wildland fuel research done in North America, and have included some done in other parts of the world. We recognize there are large amounts of data available from biomass studies which could contribute significantly to our fuels knowledge, but we have included only a few in this report. Use of the latter studies for fuels information often requires supplementary studies to provide adequate data for fuels.

The following review of fuels is organized by type of fuel—grass and forbs, shrubs, trees, down and dead, and duff—and by geographical locations. The breakdown is intended to help discuss what is known about given types of fuels in different parts of the country.

Knowledge of fuels for different ecosystems varies considerably. In a few systems, relatively complete dynamic fuel models are available, allowing a land manager to predict fuels for many years beginning at some point in biological succession. Notable examples of dynamic fuel models are chamise (*Adenostoma fasciculatum*) chaparral in southern California (Rothermel and Philpot 1973) and palmetto-gallberry (*Serenoa repens, Ilex glabra*) fuels under pine in the Southeastern Coastal Plain (McNab et al. 1978).

North Central and Northeastern United States

Fuel Types and Fire Activity

Within the North Central and Northeastern Regions are about 175 million acres of forest and uncultivated rural lands that require and receive fire protection. Four major fuel types, within which are associated 64 SAF forest cover types (Society of American Foresters 1959), are ranked by relative level of fire activity (implied fuel hazard):

Fuel type	*Acres (million)*	*SAF cover type*
Mixed Pine	21	1, 15, 20–24, 45, 47, 51, 75–79
Oak-Hickory	58	40–45, 52–65, 95
Spruce-Fir	21	30–36, 5, 12, 37–39, 46, 48, 49, 97
Northern Hardwoods	75	14, 16–69, 25–29

Fuels in these cool, moist forests are generally distributed vertically in four strata—ground, surface, shrub, and canopy. Surface, litter-borne fires, burning during spring and late autumn (bimodal fire season), are typical of the oak-hickory and mixed pine types (Haines et al. 1975). Ground fires in organic-rich soil are endemic to spruce-fir and northern hardwoods. The frequency of ground fires, particularly in the northern border States, is directly related to severity of drought. Most of the recent large fires have occurred in or were initiated in untreated logging slash (Sando and Haines 1972).

Mixed Pine

Over half the wildfire activity is associated with the mixed pine fuel types, particularly on dry or sandy sites. Pine plantations are especially susceptible to severe fire damage from time of establishment until crown closure (10 years). This susceptibility is directly related to shrub and surface fuel loadings. Herbaceous and shrub loadings of ½ to 2 tons per acre, interspersed with newly established conifer seedlings are gradually replaced by a total of 1 to 8 tons per acre of unincorporated needle cast and branchwood detritus (LaMois 1958, Crosby 1961, Dieterich 1963). Average foliage and

branchwood (≤ 3-inch diameter) fuel loadings in mixed pine crowns range from 0.09 to 0.28 tons per acre for each square foot of basal area (Brown 1966, Crosby 1961, Crosby and Loomis 1967, Sando and Wick 1972, Roussopoulos and Johnson 1975).

Stocks and Walker (1972) reported fuel consumption in jack pine slash burns. Slash ranged from about 0.2 to 0.9 lbs/ft^2 (4.4 to 19.6 tons/acre) and total fuel from 0.4 to 1.6 lbs/ft^2 (8.7 to 34.8 tons/acre).

An average total loading of harvest residue under various utilization standards is 31 tons per acre (Roussopoulos and Johnson 1973). Of this total, about 4 percent is in a < ¼- inch diameter size class; 9 percent in ¼ to ¾ inch diameter; 8 percent in ¾ to 1½ inch diameter; 6 percent in 1½ to 2½ inch diameter; 11 percent in 2½ to 3½ inch diameter; and 62 percent in ≥ 3½ inch diameter. Treatment with prescribed fire at an average intensity of 1,200 Btu/ft/sec (six fires) causes a 17 percent reduction in total loading. Changes in fuel loading within the six size classes range from a reduction of 94 percent in ≤ ¼ inch diameter to a 10 percent increase in size class 2½ to 3½ inch diameter. The increase is due, in part, to changes of larger diameters (≥ 3½ inches) to smaller size by surface charring.

Fuel consumption on several small jack pine slash plots was recorded by Chrosciewicz (1978a). The slash less than 0.8 inches in diameter had a moisture content of 10 to 25 percent, and the attached needles ranged from 9 to 21 percent moisture content. The fine slash and needles were generally all removed by burning.

Chrosciewicz (1978b) also recorded several weather and fire danger indices on 4 slash burns in central Saskatchewan during afternoons in late July and early August. Temperatures ranged from 68 to 86° F, relative humidity from 36 to 66 percent, and wind from 3 to 10 miles per hour. Fuel moisture content was 10 to 13 percent in cured needles, 12 to 18 percent in branches less than 0.8 inches diameter, 50 to 142 percent in duff not under slash and 132 to 198 percent in duff under slash. Slash was reduced from a range of 78 to 85 percent cover before burning to 0 percent after burning; duff was reduced from 99 to 100 percent cover before burning to 76 to 90 percent cover after burning.

Oak-Hickory

About 30 percent of the region's wildfire activity is associated with the oak-hickory fuel type. This activity is concentrated mostly in the southern tier States and peaks during early spring and with a lesser peak in late autumn (Haines et al. 1975).

Surface fuels, commonly consisting of L and F layers of the forest floor, are primary carriers of fire. Litter and F layer fuel loadings average about 6 tons per acre, having accumulated a maximum of 2 tons per acre annually until equilibrium is approached at 30 years (Loomis 1975 a and b, Crosby and Loomis 1974). Annual litter accumulation in mature hardwood in Missouri is maximum in November then loses about 30 percent (= 2 tons/acre) before reaching a low in August (Loomis 1975a). Dry weight of red oak (*Quercus rubra*) foliage and branchwood (≤ 3 - inch diameter) is directly related to crown diameter. Fuel loading varies from about 90 pounds per tree with 6-foot crowns to 725 pounds per tree with 18-foot crowns (Loomis 1976b).

When selective herbicides are applied to hardwoods in order to favor conifers, dead hardwood fuel loading increases about 70 percent (Loomis and Crosby 1968). It then takes about 10 years for slash and branchwood detritus to undergo 75-percent decomposition (Loomis and Crosby 1970).

In Missouri, prescribed fires burning under mature hardwoods at estimated average intensities of 120 Btu's per second per foot consume about 38 percent of the forest floor during spring and 29 percent during fall. About 16 tons per acre of litter and ≤ 4-inch diameter clearout oak slash are consumed during spring prescribed fires burning at an estimated maximum intensity of 6,500 Btu's per second per foot. The post-fire residue of approximately 10 cords per acre of charred ≥ 4-inch material is suitable for producing charcoal.

Spruce-Fir

Less than 15 percent of wild and prescribed fire activity in the Northeastern United States is associated with spruce-fir types. These types are characterized by infrequent fire occurrence, and such fire occurrence usually is a result of drought or modified fuel conditions.

Total average fuel loading for four areas (one in Minnesota and three in Michigan), which include a mixture of northern white cedar (*Thuja occidentalis*), balsam fir (*Abies balsamea*), tamarack (*Larix laricina*), white and black spruce (*Picea glauca* and *P. mariana*), is 32.7 tons per acre. Average utilization removes about 60 percent or 20 tons per acre of the larger diameter spruce-fir material. Of the total loading (unutilized), about 8 percent is classed as foliage and particles ≤ ¼ inch diameter;

14 percent as ¼ inch to 1 inch; 20 percent, 1 to 3 inches; and 58 percent, $\geq$ 3 inches in diameter.

Prescribed fire, applied at estimated intensities of 200 to 9,200 Btu's per second per foot (flame lengths of 5 to 20 ft) reduced total fuel loading (felled and cured) by 25 percent. Post-burn residue averaged a reduction in fuel loading of 90 percent in foliage and $\leq$ ¼- inch diameter particles; 81 percent in ¼ inch to 1 inch; 27 percent in 1 inch to 3 inches; and 3 percent in $\geq$ 3 inches.

Northern Hardwoods

Except during periods of severe to extreme droughts, the cool, moist hardwoods of the northern tier States are not normally subject to wildfire. These mixed hardwood types account for less than 10 percent of the region's fire activity. The occasional prescribed fire requires intensive preburn modification of fuels (felling, herbicide treatment, etc.)

Fuel loading data available for northern Minnesota and Isle Royale are of limited value for estimating fire effects. The average total loading of the community type Grigal-Ohmann (1975)—maple (*Acer* spp.)-aspen (*Populus* spp.)-birch (*Betula* spp.)-fir (*Abies* spp.) is about 34 tons per acre. Of this, 68 percent is located in the surface fuel strata, 9 percent within the shrub strata, and 23 percent in the canopy strata (Sando and Wick 1972). Information on the effect of fires on fuel reduction in this type is not currently available.

Information Needed

More than 80 percent of both wild and prescribed fires occur in less than 50 percent of the protected area. Knowledge of the dynamic effects of fire on subsequent fuel hazard is a first requisite to managing fire in the Northeast, particularly for the 79 million acres of pine and oak-hickory types. Does treatment with fire, either intentional or unplanned, accelerate or deter decomposition of post-burn residue and the implied fuel hazard?

Although the level of fuel (hazard) reduction by fire is directly proportional to the fire's intensity, the level of potential productivity (site) of both conifer and oak stands managed for timber production appears to be inversely proportional to the fire's intensity. Identifying the optimum levels of fire intensity that will benefit both hazard reduction and the beneficial net effects on site productivity is of prime importance in the Northeastern United States.

Southern and Southeastern United States

Fuel Types and Fire Activity

The southern area of the United States is generally considered to include 13 States, bordered by and including Virginia, Kentucky, Arkansas, Oklahoma, and eastern Texas. The region is generally thought of as dominated by the southern pines. This broad forest type consists of four major and seven minor species. In the mountain region of the southern Appalachians and in low lying wet areas, however, pure hardwood or mixed conifer-hardwood forests predominate.

Generally, the climate of the Southeast is characterized as having long warm summers, mild winters, and adequate rainfall throughout the growing season. Typically, a 2- to 3-week period of drought occurs in the late spring. Coinciding with this brief dry period is a short interval of considerable fire danger which often takes place before spring growth begins and fuel moisture content increases. The larger wildfires usually occur in remote areas where ground access is restricted.

The prescribed burning season in the southern pine type begins in December and extends through March. Most burning is for hazard reduction and is carried out on a 3- to 4-year rotation. When high fuel consumption is desired, site preparation burns are made during the summer months. Other uses of fire in the South include various wildlife management practices, disease control, and understory hardwood control.

A discussion of various fuel types in the southern area will be based on forest types recognized by the Society of American Foresters (1964).

Fuel type	*SAF cover type*
Upland hardwood	40–42, 52–56, 87, 88
Bottomland hardwood	
Sand pine	69
Longleaf pine	70, 71

Fuel type	*SAF cover type*
Shortleaf pine	75, 76, 80
Virginia pine	78, 79
Loblolly pine	80–82
Slash pine	83–85
Pond pine	98

Upland Hardwood

Except in the mountains, most upland hardwood types occur in mixed stands with the southern pines. Fuels information is generally limited to fire case histories or estimates of biomass, with no available references on fire effects on fuels.

DeCost et al. (1968) reported the Gaston Fire that burned 7,400 acres in pine plantations and upland oak hardwood stands in the Sand Hills region of South Carolina. Before the fire, estimates of fine fuels loading ranged from 3 tons per acre to 11 tons per acre. Because of unusually dry weather, moisture content in cured fuels averaged below 10 percent, and available fuel approached 100 percent of total fuel. During the period of main fire spread, fire intensity ranged from 2,500 to 3,000 Btu's per second per foot of fire front. One growing season following the fire, most of the top-killed scrub oaks had developed profuse basal sprouts, which markedly increased green fuel loading and reduced the depth of the fuel bed.

Several studies have been reported that concern estimates of individual tree biomass. Phillips (1977) presented equations, based on diameter, for predicting tree component weight of a number of Piedmont understory hardwood species. In a similar study, Edwards (1976) determined biomass of individual hardwood trees based on ground line diameter.

General estimates are available on the production of residue from logging operations. Martin (1976) presents data for many Appalachian hardwoods. Depending on the type of harvesting practice, logging volume of residues can range between 33 to 2,312 cubic feet per acre. Toole (1965), studying hardwood deterioration, found that most fine fuels had fallen by 4 years after logging. Larger branches and bole wood had settled to the ground by 7 years. Rate of decomposition did not vary with soil type, drainage, elevation, or precipitation amounts. Cottonwood (*Populus deltoides*) was not a fire hazard after 3 years, while other species required about 6 years to become less of a fire hazard.

Sand Pine

Sand pine (*Pinus clausa*) is very limited in distribution and has little economic value compared to other species. Most sand pine grows in central and western Florida on deep, sandy, infertile soils. Even though sand pine is considered a fire species, very little has been reported on its fuels, especially loadings. Hough (1973) conducted a study of the flammability of sand pine fuels as related to various chemical and physical characteristics, and found seasonal changes in fuel flammability were influenced by foliage phosphorus content, ether extractives, and moisture content. In late winter, moisture content reaches an average minimum of 125 percent and other extractives peak at about 13 percent of dry weight.

Wildfires may become very intense because of the foliage extractives and the dense, closely spaced stands. Crowning can occur easily but will not be consistent because of varying fuel conditions.

No fuel loading information seems to be available. Using estimates of total forage yield to approximate available fuel, loadings will range from 17 to 751 pounds per acre, depending on site and understory vegetation (Lewis 1973). The forest floor may resemble that of shortleaf pine (*Pinus echinata*) because of similar foliage characteristics. Total biomass would be expected to be less than for shortleaf because of the generally poorer growing sites.

Longleaf Pine

The longleaf pine (*Pinus palustris*) forest is considered a fire subclimax. Over the millenia, periodic wildfires maintained nearly pure forests of longleaf on the coastal plains from southern Virginia to eastern Texas, and also on exposed ridges and slopes of the Appalachian Mountains in Alabama and northwest Georgia. The virgin longleaf forests typically had an understory comprised predominantly of grasses—mainly bluestems (*Andropogon* sp.) in south-central Alabama and westward and wiregrass (*Aristida stricta*) to the east. After settlement, longleaf forests were often deliberately burned to promote forage growth for open range cattle grazing. This practice, unknowingly, helped maintain longleaf, and is partly responsible for the second growth forests that still exist. Prescribed burning, as a forest practice, had its beginnings in the longleaf pine type.

Principal fuels in longleaf forests of the rolling middle coastal plain uplands are the grasses, plus

some forbs, and pine needle litter. Hardwoods and shrubs are important contributors to understory biomass, primarily in those areas where fire was successfully excluded for a number of years. On these well-drained upland pine sites, with fire exclusion, the understory will become dominated primarily by oaks, dogwood (*Cornus florida*), hickory, blackgum (*Nyssa sylvatica*), and sweetgum (*Liquidambar styraciflua*). With periodic fire, hardwoods and shrubs are largely confined to drainageways that are normally too wet to burn. Heaviest understory fuel accumulations are found on the wet flatwoods sites of the lower coastal plain. Palmetto (*Serenoa repens*) and/or gallberry (*Ilex glabra* and *I. coriacea*) are the principal understory species. Both recover rapidly from winter fires.

For the most part, total fuel weights in Coastal Plain longleaf stands are comparatively light. Dry weight of organic material on the forest floor range from 2,600 to 4,300 pounds per acre under pine overstories ranging from 10 to 50 square feet of basal area per acre (Boyer and Fahnestock 1966). Grass drops from 1,100 to 500 pounds per acre as stand density increases, while pine needle litter rises from about 500 to 3,000 pounds per acre. Needle litter accumulation did not exceed 2 years production in any stand. Debris from hardwoods and brush amounted to only 200 pounds per acre, and large woody material averaged 800 pounds per acre.

According to another study in the same area (Gaines et al. 1954) the dry weight of herbage (grass plus forbs) on the forest floor declined from 1,000 pounds per acre in clearings to 700 pounds under an overstory of 40 square feet of basal area and down to 475 pounds under an overstory of 110 square feet. Needle litter increased with stand density to a maximum of 8,000 pounds per acre. The amount of herbage was related more directly to amount of litter than to overstory density. The amount of herbage was also affected by site quality. Sites with a clay subsoil had about twice the herbage as deep sandy soils.

Fires have an impact on both the weight and composition of the forest floor. Much of the accumulated litter and dead herbage (rough) is removed. Loss of this material is compensated for, at least in part, by an increase in the growth of grass and forbs. According to some early studies in south Mississippi (Green 1935, Wahlenberg et al. 1939) the amount of herbage produced on acres burned annually is double that on unburned areas. Apparently, the grasses respond to release from the inhibiting effects of dead organic material, and perhaps also to nutrients obtained from the ashes. A recent study in southwest Alabama[1] revealed a 30 percent increase in herbage yield on biennially burned areas versus similar unburned areas (710 to 920 pounds per acre, respectively). The pine overstory averaged 40 square feet of basal area per acre.

Burning of forest ranges in Louisiana improved both the quantity and quality of the native grasses (Duvall 1962, Duvall and Whitaker 1964, Duvall and Linnartz 1967, Grelen and Epps 1967). Burning aided grass production by removing litter and dead grass and also by topkilling shrubs and small hardwoods. The positive effects of fire lasted through the three succeeding growing seasons. On these open areas, herbage production averaged 4,400 pounds per acre after a fire.

The studies reported above were all in Alabama, Mississippi, and Louisiana where the ground cover is dominated by bluestem grasses. Wiregrass in the eastern part of the longleaf pine range is also stimulated by burning (Biswell et al. 1944, Lemon 1946, Lewis and Hart 1972). Winter burning can nearly double the yield of wiregrass forage types.

Little information is available about the amount of forest fuels comprised of small hardwoods, shrubs, and logging slash. Fuels derived from these sources have the potential to greatly exceed the maximum from herbage or litter. In Florida, the presence of gallberry or palmetto added about 2 tons per acre to the fuel load (Bruce 1951). He observed fuel loads ranging from 1½ tons per acre on open areas 1 year after a burn to 22 tons per acre under dense pine stands with a palmetto understory unburned for 10 or more years. Within this same type Sackett (1975) reported total fuel weights ranging from 5,731 pounds per acre 1 year after a fire to 18,450 pounds per acre after 12 years without burning. Saw palmetto made up the largest fraction of understory fuel in these 45-year-old north Florida longleaf stands. Wherever such fuel loads occur, untimely wildfires pose a real and constant threat. Hazard reduction burns at intervals of no more than 5 years will substantially reduce the risk of destructive wildfires (Davis and Cooper 1963).

Logging slash remaining after a heavy thinning is also a hazard, but only for a relatively short pe-

[1] Maple, W. R. 1975. Longleaf pine stands support multiple use. Unpublished manuscript. U.S. Dep. Agric. For. Serv. South. For. Exp. Stn., New Orleans, La., 17 p.

riod of time. Two growing seasons after clearcutting, the presence of residual logging slash does not significantly add to the impact of prescribed fires in clearings (Boyer 1974).

Because of the long association of fire with the longleaf pine forests, more information on fire effects has been acquired for this type than any other. Significant gaps in our knowledge remain, however. With respect to fuels, we need to learn more about the quantity and type of fuels accumulating within pine stands in the absence of fire, particularly as related to soil-site conditions. A special problem is the rate of fuel accumulation in pine plantations established on prepared sites. The necessity for, and frequency of, hazard reduction burns will be tied to this kind of information on forest fuels.

Shortleaf Pine

After loblolly (*Pinus taeda*), shortleaf (*P. echinata*) is the most abundant of the southern pines. Its range, for the most part, coincides with loblolly pine except that shortleaf extends farther north into Missouri, Kentucky, and West Virginia and it does not occur farther south than the Florida panhandle. The species is concentrated largely in the Ouachita Mountains of Arkansas and in the Piedmont Plateau from Virginia to Alabama. It is also common in the middle Coastal Plains from Alabama to east Texas. Oak and hickory are the principal hardwood associates of shortleaf pine throughout its range.

Most of the available fuels information for shortleaf pine has been derived from shortleaf-loblolly pine-hardwood stands. Therefore, some of the information on loblolly pine types may also apply to shortleaf pine. The literature related to understory fuel sources in shortleaf pine types provides a sharp contrast to that for longleaf pine types. Instead of grass and needle litter, small hardwoods and shrubs have received most of the attention. Fire is not closely associated with these types. Shortleaf and loblolly pines, when small, are more susceptible to fire damage than associated hardwoods, and do not occur naturally in areas frequently burned. As rapid-growing pioneers on old fields, blowdowns, or severe burns, these pines have an early competitive advantage over hardwoods. The latter soon occupy most, if not all, the understory growing space. On good sites, little room is left for grasses and forbs. The hardwood understory does not provide a favorable environment for fire except, perhaps, under exceptionally dry conditions. Herbage yield is closely associated with stand density. In one study (Halls and Schuster 1965), total herbage in a shortleaf-loblolly-hardwood forest ranged from slightly above 600 pounds per acre with 20 percent tree cover to less than 200 pounds per acre with 100 percent cover.

As in all pine stands, the most flammable fuel present is the needle litter. Litter accumulation is related to pine basal area (Crosby 1961), and its weight alone gives the best measure of available fuel for forest fires.

The reported uses of prescribed fire in this timber type are primarily for hardwood and brush control rather than hazard reduction. Abundant needle litter fuel is an asset in this situation because better control of understory brush can be obtained (Grano 1970). Repeated growing season fires are more effective in eliminating hardwoods (up to 4.5 inches d.b.h.) than dormant season fires (Ferguson 1957, 1961; Harrington and Stephenson 1955). When the hardwood component of the stand is reduced through fire, there is an increase in legumes and other forbs (Hodgkins 1958).

Cultural treatments resulting in the greatest increase in fuel load in the loblolly-shortleaf pine type are—first, logging with its resultant slash and, second, destruction of the hardwood understory with fire or herbicides or both. The period of increased fire risk from these fuels is limited, however. There is little fire hazard from logging slash after 3½ years (Siggers 1935). Fire risk from deadened hardwoods may be high for 3 to 7 years after treatment, depending on the number and size of the trees (Loomis and Crosby 1970).

Any additional information on types and amounts of fuels in shortleaf pine forest ecosystems will be most useful. There are two principal applications for this knowledge. One is in estimating wildfire hazard. The other is for developing prescribed fire as a cultural tool in the management of shortleaf pine.

Virginia Pine

Virginia pine (*Pinus virginiana*) typically occupies drier sites and occurs in lower elevations of the Appalachians. It may be prevalent on poorer sites throughout the Piedmont Plateau and extend over to eastern Kentucky and Tennessee.

Information on the effects of fire on fuels of this species is almost entirely limited to estimates of biomass. A study by Madgwick (1968) included estimation by regression of biomass of various tree components in a 17-year-old, open-grown stand.

Estimates of standing fuels indicated that about 23 tonnes per hectare may be present in a typical stand, excluding the tree boles. About 6.4 tonnes per hectare of the total are in needle fascicles.

Loblolly Pine

Loblolly pine (*Pinus taeda*) has the widest range of the southern conifers, extending from Delaware to east Texas. Most of the work reporting the effect of fire on fuels in the loblolly type is available from the literature on fire effects on vegetation. A very preliminary dynamic model of forest floor accumulation is presented in the Southern Forestry Smoke Management Guidebook (Johansen et al. 1976). However, this model was derived from a special case of the more complex model for slash pine, and therefore should be applied with caution.

Fuel loading in undisturbed loblolly plantations was studied by Brender et al. (1976). Results show weight of the forest floor is related to stand basal area by the relationship:

$$\text{Loading (lb/acre)} = 4431e^{(.008BA)}$$

where e is the natural logarithm and BA is basal area of the loblolly plantation in square feet per acre. Equilibrium of the forest floor is reached in about 17 years with approximately 17,000 pounds per acre of fuels.

Numerous references are in the literature reporting the effects of prescribed burning on vegetation. Some of these may be used to quantify the effect of fire on fuels in the Coastal Plain and Piedmont regions of the South. Winter fires used for hardwood control tend to decrease litter, grass, and small shrub fuels, while increasing loading of dead fuels averaging less than 1 inch in diameter (Lotti et al. 1960). The main fire response variable in their work was change in tree stem numbers per acre. Neither loading nor fire intensities information is available. Summer fires in pine-hardwood stands will increase loadings of dead fuels up to 2 inches in diameter (Lotti 1959). Lotti reported that a series of annual winter burns will eliminate almost all live understory fuels. Biennial fires are less effective in killing hardwood vegetation, and hence will cause less standing dead fuels.

Winter burns have been reported to reduce the forest floor weight by about 66 percent (Jorgensen and Hodges 1970). Preburn fuel weights of the F and H forest floor layers in 1-, 8-, and 20-year-old roughs were 0.137, 0.356, and 0.422 grams per square centimeter.

The effect of winter burning on grass fuels and forbs is to significantly increase annual yields while causing an immediate decrease of live and dead material (Lewis and Harshbarger 1976). Fine fuels were increased up to 23 times, compared to areas of fire exclusion, ranging from 27 pounds per acre on unburned plots up to 608 pounds per acre on annual winter burns. Annual summer fires were found to reduce total ground cover to a greater degree than other treatments—to less than 30 percent.

Tables for estimating biomass, or total fuels, of various sized loblolly pine have been developed. Wade (1969) reported the following equation for predicting crown fuels from trees in the Piedmont or Coastal Plains ranging from 6 to 18 inches d.b.h.:

$$\log Y = 2.538(\log X) - 0.573$$

where Y is pounds of crown weight and X is d.b.h. in inches. Smalley (1973) presents data on trees from 1 to 14 inches d.b.h. for both loblolly and shortleaf pine. Prediction equations for trees up to 20 inches d.b.h. were reported by Clark and Taras (1976).

Somewhat less information has been reported on fire effects on loblolly fuels in the Piedmont. A comprehensive review of general effects is given by Brender and Cooper (1968), who describe increases in dead fuels 1- to 2-inches d.b.h. following winter and summer prescribed fires. Summer or winter burns killed, respectively, 80 percent and 73 percent of an average of 19,700 hardwood stems per acre initially present. Fuel consumptions ranged from 38 to 53 percent of preburn loadings, which ranged from 4,821 to 6,345 pounds per acre. Back fire intensity was 1,232 Btu's per minute per foot in winter and 1,200 Btu's per minute per foot in summer. Strip headfire intensities were 8,448 Btu's per minute per foot in winter and 11,200 Btu's per minute per foot in summer.

Hodgkins (1958) reports on the effects of fire on loblolly fuels with much the same findings. However, he studied the effect of topographic position and reported no significant differences between ridge top or side slopes for abundance of grass fuels. Grass cover regained its initial advantage in 2 years after burning. Mortality of shrub fuels was much higher after initial burns than after follow-up fires. This would also indicate an increase in loadings of dead fuels.

Logging slash reduction by burning in the loblolly type was studied by Cushwa et al. (1969). A preburn

inventory estimated debris loading at 7.5 tons per acre and grass and litter at 5 tons per acre. No postburn data were collected on fuel loading. Following the burn, the number of living plants on the 3-acre study site increased from 908 to 1,808 in one growing season.

Slash Pine

The slash pine (*Pinus elliottii*) forest forms the most extensive conifer type in Florida and southern Georgia, where prescribed fire is used on a regular basis for a number of objectives. During the winter months, burning is typically used for hazard reduction, seedbed preparation, and wildlife habitat improvement. Longleaf pine is often found growing in the slash pine type.

The general effect of fire on slash pine fuels is perhaps best illustrated in a study reported by Davis and Cooper (1963). Their findings revealed that fuels could be effectively reduced by fire for up to 5 years, thus lessening the chances of a damaging high intensity wildfire. A relationship between fuel accumulations over time and intensity, which was measured as flame length, is presented as:

$$Y = 2.07 + 3.44(X)$$

where Y is height of char (or flame) in feet and X is age of rough in years.

Dynamic models for fuel loading of the forest floor and understory vegetation have been developed for ages of rough to 25 years (McNab et al. 1978). Inputs into the regression models are based on easily measured variables such as age of rough, stand basal area, height of understory, and percentage of palmetto in the understory. Outputs from the models are in terms of fuel loadings for the various time lag classes used in the National Fire Danger Rating System (Deeming et al. 1972). Total loading on an average site at 20 years is estimated at 5.2 kilograms per square meter.

Methods to estimate fuel loading consumed in prescribed burns have been developed by Hough (1968), based on preburn fuels and fuel moisture content. In these tests, preburn fuel loading of litter ranged from 4.5 to 16 tons per acre and understory vegetation from 2.5 to 3.5 tons per acre. Total fuel reduction was similar for both heading and backing prescribed fires—averaging 56 percent. Backfires consumed more litter fuels, however, Fire line intensities of backing fires ranged from 5 to 124 Btu's per second per foot. Hough and Albini (1978) have developed models for predicting fire behavior in slash pine fuels that serve as inputs into the National Fire Danger Rating System, based on variables for the dynamic fuel model, together with season of the year and midflame windspeed. Flame lengths up to 2.5 feet may be predicted, and rates of spread, for winter fires, up to 45 feet per minute.

Sackett (1975) provides results of static models of prescribed burning on understory and forest floor fuels in South Carolina and Florida. In Florida, available fuels ranged from 2 tons per acre on a 1 year rough to 3 tons per acre at 12 years. Available fuels were heavier in South Carolina, where they ranged from 2.5 to 5 tons per acre for the same ages of rough.

The effect of burning palmetto and gallberry fuels is described by Hough (1965). He found that up to 55 percent of dead fuels and 65 percent of vegetative fuels were reduced by prescribed backing fires. A method is also presented for using a regression relationship to estimate vegetative dry weight of palmetto by measuring foliage cover from photographs.

Observations on the effect of prescribed burning on living tree and shrub fuels is described by Grelen (1976). Usually by 5 years, trees were large enough not to become part of the available fuels in carefully controlled fires. Van Loon and Love (1973) reported that mainly forest floor fuels were consumed in a series of prescribed burning tests in 8-year-old slash pine plantations. Intensities averaged less than 25 Btu's per feet per second and preburn fine fuel loadings ranged from 2.4 to 4.7 tons per acre. Fuel reduction averaged about 45 percent.

Estimates of overstory fuels are commonly made by extension of biomass measurements of small samples of trees. For slash pine, equations for estimating various fuel components were developed by Clark and Taras (1976). Presentation of overstory fuels in the form of logging debris, with classification based on the National Fire Danger Rating System, were made by Johansen and McNab (1977) for slash pine. Regression equations based on mean stand diameter were developed to estimate residues per cord of standing timber. Loading may average from 583 to 1,232 pounds of residue per cord for the stands studied, which had a diameter range of 5 to 11 inches d.b.h.

Grass fuels beneath pine overstories tend to react in a similar manner to fire regardless of the tree species. Duvall and Linnartz (1967) presented data showing almost complete reduction in grass fuels following prescribed burns in grazed woodlands.

Fuels varied widely depending on grazing intensity. Annual production on ungrazed areas averaged 1.4 tons per acre. Litter averaged 2.5 tons per acre. Following burning, litter accumulation regained preburn loading in about 3 years. The rate of grass fuel accumulation has been presented in a model based on age of rough (Johansen et al. 1976).

Pond Pine

Pond pine (*Pinus serotina*) is a fire species as indicated by its serotinous cones. This species is of importance in eastern North Carolina and in low lying areas of South Carolina. Typically, pond pine is associated on organic soils with a dense scrubby understory of evergreen and deciduous vegetation. This vegetation association is referred to as the pocosin fuel type. Some of the larger and more difficult to control wildfires in the East have occurred in pocosin fuels. Most wildfires in the pocosins occur during the early spring and before the evergreen vegetation has increased its moisture content through spring growth (Blackmarr and Flanner 1975).

Fuel information for pond pine crowns is available from regression models (Wendel 1960). Total dry weight of crown foliage may be estimated by the equation:

$$W_{df} = 0.486\ (d.b.h.)^{1.697}$$

where W_{df} is weight of ovendry foliage and $d.b.h.$ is diameter breast high outside bark. The loading of foliage and branchwood may be estimated by:

$$W_{dc} = 0.369\ (d.b.h.)^{2.390}$$

where W_{dc} is the weight of the ovendry foliage plus branchwood in pounds. Wendel (1960) also points out that the energy released by a fire burning in pond pine crowns would be increased by 11 percent compared to an understory fire alone. This increase would be the result of available crown fuels.

The effect of fire on pond pine and associated pocosin fuels is explained in detail by Wendel et al. (1962) for various understory fuel types. A blowup potential was developed for classifying various fuels based on a number of factors, including available fuels, combustion period, burnout time, and spotting potential.

A system of discrete pocosin fuel types based on loading was developed by Wendel et al. (1962) and is being used by personnel in several Southern States; however, no dynamic fuel models are available for fire damage prediction. Evaluation of ovendry loadings in various pocosin fuels is as follows:

Fuel Type	Loading of *Vegetation*	*Litter*
	- - - tons/acre	- - -
Wiregrass	1.5	2.9
Low pocosin (open)	2.1	3.6
Grass-low brush	2.9	3.6
Low reeds-grass	3.9	2.6
Low pocosin (dense)	4.0	4.4
Brush-sand ridge	4.1	4.4
Medium reeds-brush	4.7	4.0
Low brush-grass	2.9	5.9
Medium brush-grass	4.8	4.6
High reeds	6.1	4.0
Very high reeds	8.5	4.7
High pocosin	6.0	9.0
High brush	12.0	5.4
High brush-swamp	15.6	5.4

No method of estimating available fuels in the pocosin fuel types was given.

Wade and Ward (1973) applied earlier findings on pocosin fuels to their analysis of the 29,300-acre Air Force Bomb Range Fire which burned in 13-year-old pond pine and dense pocosin understory fuels. Preburn fuel loadings ranged from 6.4 to 15.7 tons per acre and from 0.2 to 1.1 tons per acre after burning. During the main fire advance, line intensity averaged 18,000 Btu's per second per foot. In addition to almost complete defoliation of the pond pine overstory and consumption of the understory, organic soils in various areas were consumed to depths of from 12 to 18 inches.

Research Needs and Priorities

In the South, most available information on the effect of fire on fuels is limited to those fuel types where fire is an important silvicultural tool. These types include slash, longleaf, shortleaf, and loblolly pines. However, adequate information to assist the land manager in making decisions regarding fire use is available only for slash pine and, possibly, longleaf.

A definite need exists for better fire-effects information for the loblolly pine type, especially in the Piedmont region where prescribed burning increasingly is being used. For loblolly pine in the Coastal Plain, very little data are available con-

cerning fuel loading modeling or fire behavior. Additional work should be done in the sand pine type because of the frequent occurrence of fire in this fuel type. For the pond pine-pocosin type, the only data available are in the form of case histories and static estimates of fuel loadings.

A priority evaluation of study in fire effects for the southern forest types would be:

Type	*Priority*
Loblolly pine	High
Pond pine-pocosin	High
Shortleaf pine	Medium
Sand pine	Medium
Virginia pine	Low
Upland hardwoods	Low
Bottomland hardwoods	Low
Longleaf pine	Low
Slash pine	Low

Southwestern United States

Introduction

In reviewing the available information on the effects of fire on southwestern fuels, Arizona, New Mexico, and portions of southern Colorado and southwestern Texas were considered; wildfires were distinguished from prescribed fires, and the available knowledge was summarized by cover type using the following general categories:

Fuel Type	*SAF Cover Type*
Ponderosa pine (*Pinus ponderosa*)	237
Mixed conifer	210, 211, 237, 239
Pinyon-juniper	239
Chaparral	
Semidesert grass-shrub	
Southwestern Texas semidesert	

A review of the literature reveals only a limited amount of information that includes—in addition to pre- and post-fire fuel inventories—a description of the fire in terms of intensity, spread rates, fuel moistures, etc., that are responsible for the fire effects. As might be expected, most of the work has been in ponderosa pine because of its economic importance, the frequent occurrence of wildfires in this type, and the fact that prescribed fire is used rather extensively in the type. Mixed conifer represents a type for which fire effects studies are needed but virtually no information is available. Studies of the effects of fire in chaparral and the semidesert grass-shrub communities have been rather common but descriptions of the fire in terms of its effect on the fuel are lacking.

Fuel Types and Wildfire

Ponderosa Pine

The Willow Fire occurred on the Chevelon District of the Apache-Sitgreaves National Forest, Ariz., and burned 2,850 acres between June 17 and 19, 1975 (Dieterich 1976). The fire burned during a critical period of fire weather that was made more difficult by the presence of a lowering jet stream. Winds averaged from 20 to 35 knots with gusts to 40 knots; relative humidity was from 15 to 25 percent; and fuel moisture was from 3 to 5 percent.

Fuels were inventoried on 11 plots in the vicinity of the fire; and loadings, including litter, varied from 18 to 54 tons per acre depending on the degree of slash treatment.[2] In an effort to determine the amount of fuel consumed by the fire, paired plots were established in a sapling-pole stand that was bisected by a fireline leaving a division between burned and unburned area. Trees averaged from 3 to 4 inches d.b.h. (range from 1 to 8 inches) and there was no thinning slash on the ground. Heavy fuels were present. Down and dead woody material amounted to 42 tons per acre and 10 tons per acre of litter were inventoried on the unburned plot. On the adjacent plot that had been burned, the inventory indicated that 13 tons, or about one-third, of woody fuel had been consumed and that 9 tons (or about 90 percent) of the litter were consumed, for a total of 22 tons per acre consumed. Of this 22 tons, it was estimated that from 8 to 12 tons of fuel were consumed in the fire front, producing intensities

[2] Unpublished office report. On file with the Fuel Management Project, Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.

that ranged from about 4,000 to 6,000 Btu's per second per foot (Brown and Davis 1973). Crown consumption was observed up to 35 feet high and crown scorch extended up to 40 to 50 feet.

The Huffer Fire occurred on the Long Valley District of the Coconino National Forest on June 16, 1977.[3] Burning conditions during the major run were typical of the spring weather that is frequently responsible for large fires in the ponderosa pine type—southwesterly winds averaging from 5 to 15 knots with gusts to 22 knots; relative humidities throughout the burning period between 13 and 30 percent; air temperatures in the low 80's; and fuel moistures averaging 3.8 percent.

Adjacent to the fire, litter loading averaged 15 tons per acre (basis: 6 sampling sites involving 10 subsamples at each site). Woody fuels averaged 18 tons per acre (basis: six sites, four transects per site).

Woody fuel was sampled at five sites within the burned area following the fire and averaged 4.5 tons per acre, or a 75 percent reduction in the woody material. Litter fuel consumption was so complete that it was felt that postfire litter sampling was unnecessary. A summary of average fuel consumption is shown below:

	Before burn	*After burn*	*Reduction*
	- - - tons/acre - - -		percent
Litter fuels	15	<1	90–100
Woody fuels	18	4.5	75

Assuming that 5 tons per acre of litter and 6 tons per acre of woody fuel were consumed in the fire front (0.5 lbs/ft^2), and using an observed rate of spread of 65 chains per hour (1.19 ft/sec), Bryam's formula produces a fireline intensity of 4,760 Btu's per second per foot.

The Rattle Burn occurred on the Coconino National Forest from May 7 to 9, 1972 (Campbell et al. 1977). In assessing the effects of this wildfire, the following assumptions were made concerning fuel loadings prior to the fire: slash fuels—20 tons per acre; litter fuel—14 tons per acre; woody fuels in addition to logging slash—19 tons per acre; for a total of 53 tons per acre.

It was estimated that 20 tons of fuel per acre (0.93 lb/ft^2) was consumed in the flaming front, and that the fire spread at a rate of 16.4 chains per hour in the "moderate" intensity fire and 70 chains per hour in the "high" intensity fire. The fireline intensities were computed as being approximately 2,500 and 10,000 Btu's per second per foot, respectively, for the "moderate" and "high" intensity portions of the fire.

Fuels were not sampled following the burn, but it was determined that in the "moderate" intensity fire 50 percent of the pulpwood-size trees and 7 percent of the sawtimber were destroyed. The more "intense" fire destroyed 90 percent of the pulpwood and 50 percent of the sawtimber. Herbage production increased approximately threefold on the moderately burned area (from 450 to 1,275 lb/acre) and fourfold on the more intensely burned area (from 450 to 1,650 lb/acre). The fire reduced the ground cover (vegetation and litter) from 93 percent on the unburned portion to 39 percent and 23 percent, respectively, on the moderately and intensely burned watershed.

Mixed Conifer

No references available.

Pinyon-Juniper

While there have been no quantitative measurements made on the effects of wildfires on pinyon-juniper fuels (i.e., fuel available, fuel consumed, fuel created, etc.), there have been some studies of the effects of wildfire on plant succession, species composition, and density changes that may be loosely interpreted in terms of changes in fuel loading.

In a study by Arnold et al. (1964), 16 wildfires were studied to verify dates of burning and to record subsequent ecological changes. They found that the fires occurring in flat to gently rolling terrain tended to burn clean—consuming available ground fuels, killing most of the trees, but leaving the dead skeletons of the trees standing. Ground fuels are rarely heavy in pinyon-juniper stands—probably never exceeding 1 to 3 tons per acre. In rougher terrain, islands of unburned trees were left on hills and ridges where fuel continuity was too sparse to support fire spread.

A wildfire on the Hualpai Indian Reservation in 1953 destroyed nearly 100 percent of a dense pinyon-juniper stand and effectively removed all the vegetation and litter. The fire burned with strong winds, low relative humidities, and air temperatures in the 90's (Arnold et al. 1964).

[3] Unpublished office report. On file with the Fuel Management Project, Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.

In contrast, an adjacent unburned area had a tree and shrub cover of from 37 to 46 percent and a litter cover of from 50 to 60 percent. Understory vegetation was sparse. Trees averaged 360 per acre, of which 40 percent were pinyon (*Pinus edulis*). Following the fire, annual plants invaded, became abundant the second and third years (no estimate made of biomass produced), then began to decrease during the fourth year as perennial grasses became established.

On another burn dating back to 1875, near Grand Canyon Village, Ariz., a pinyon-juniper stand was converted to a big sagebrush (*Artemisia tridentata*) type. Numerous islands of unburned trees indicate that the original stand had not been uniform in density or composition. It appeared that not only was the pinyon-juniper stand replaced by big sage, but that the sage tended to restrict the development of native grasses. (Again, no quantitative estimates were made of fuel loadings before or after the fire.)

In summary, the successional recovery after fire in dense stands of pinyon-juniper begins with the establishment of annuals. The annuals peak in the second to third year; annual-perennials are more abundant than annuals. Shrubs become important the fourth year and continue to increase until the sixth year. At this point succession appears to take one of two courses: A perennial shrub stage will develop if shrubs are present; if shrubs are absent, the perennial forb-grass stage may give way to perennial grasses. If a shrub stage develops, it may be converted to a grassland stage by a second fire. When protected, both shrub and grassland stages will be reinvaded by the pinyon-juniper in its effort to become reestablished as the climax type.

Chaparral

Few quantitative measurements have been made on the effects of wildfire on chaparral fuels in the Southwest, nor have there been any efforts to measure fuel loading in the Arizona chaparral stands. Converting stands of chaparral to grassland can result in some significant increases in forage yield (herbaceous fuels) with a corresponding reduction in chaparral biomass.

In 1959, a wildfire burned over the chaparral-covered Three Bar Experimental Watersheds located on the Tonto National Forest northeast of Phoenix, Ariz. Three reports summarize this work (Hibbert and Ingebo 1971, Hibbert 1974, Glendening et al. 1961).

Although shrub crown cover tended to recover rather quickly after the fire, the 75 percent crown cover that was present before the fire had still not been reached 16 years following the initial removal (65 percent recovery). These results are consistent with estimates made by those experienced in handling wildfires in chaparral[4] who indicate wildfires that burn into old chaparral burns (up to approximately 20 years old) show a definite change in burning characteristics—spread is not as rapid and flame lengths are reduced. The change would appear to be related to the proportion of dead-to-living material in the crowns of the shrubs.

On Three Bar "C," an experimental watershed that was converted to grass following the wildfire, and has since been maintained by the use of prescribed fire, the herbaceous production was significant. Peak production was reached 8 years after the fire when 2,600 pounds of dry matter per acre was produced, about half of which were introduced grasses. Grass production from 1963 to 1968 averaged nearly seven times that which was produced on the control watershed. Shrub cover has remained at less than 10 percent. This conversion also resulted in an increase in water yield that was nearly 85 percent of what might normally be expected on the area.

In another study of a wildfire by Pond and Cable (1962), it was found that in only 7 years chaparral crown cover was approaching the density of an adjacent unburned area. Grass cover, seeded following the burn, continued to increase within an exclosure for 5 years following the fire. On an adjacent area, not excluded from grazing, the basal cover of grasses was lower 5 years after the fire than it was the year after the burn was seeded.

In June 1956, a wildfire burned over 18,000 acres, much of which was Arizona chaparral, on the Prescott National Forest near Dewey, Ariz. (Pase and Pond 1964). Vegetative recovery was followed for six growing seasons and the study provides some quantitative documentation of vegetation (fuel) recovery following the fire. Reduced to essentially zero by the fire in 1956, crown canopy and accumulated weight of shrubs were still increasing six growing seasons after the fire, reaching 4,810 pounds on the area or averaging about 780 pounds accumulated weight per year. Shrub live oak (*Quercus turbinella*) remained the dominant species. Production of herbaceous fuels following the fire was

[4] Personal communication with personnel on the Tonto and Prescott National Forests.

small, reaching a peak of about 200 pounds per acre 4 years after the fire. On plots sprayed to control brush sprouting, herbaceous (grass) production reached about 900 pounds per acre 5 years after the fire.

A study by Pond (1971) provides a reliable record of the persistence of several chaparral species over time. Although fire did not play a role in the changes observed in any of the species, apparent changes in the ratio of live to dead material in the crowns of the shrubs were recorded. For example, of eight separate shrub live oak plants tagged for observation in 1920, only one had died when the final counts were made in 1967—47 years later! An increasing amount of dead material was evident during each of the four observations made of the plants between 1927 and 1967.

There is only one indirect inference concerning the effects of wildfires on fuels in a reference by Brown and Boster (1974) and that concerns the natural fire cycle of the species. Their theory maintains that because the fire suppression effort has been so effective (in the absence of any large-scale use of prescribed fire), most of the chaparral type is approaching, or has exceeded, the 20-year age when the chaparral stands may be expected to burn again. Continued suppression efforts will ensure that a large number of small fires will be suppressed but large fires in overmature chaparral stands are inevitable and will continue to occur.

Semidesert Grass-Shrub

As with many of the southwestern fuel types, there is little quantitative data available on the effects of wildfires on fuel accumulation and consumption. Fuel changes are expressed only indirectly in terms of changes in species composition and herbage weights of the various grass or shrub species. In spite of this apparent lack of information, some data is available that is closely related to fuel accumulation and consumption in the semidesert plant communities.

Cable (1972) indicates that June wildfires occurring during the hottest, driest part of the year, have the largest impact on the semidesert shrubs. There appears to be a direct relationship between the herbaceous fuel loading (grass cover), fire intensity, and resulting mortality of the semidesert shrub species. Sprouting may also be influenced by fire intensity.

The herbage production from annual grasses was about twice as high on burned as on unburned areas in wet years, but there was little difference in herbage production during dry years.

Nearly all species of perennial grasses decreased the first growing season following a June wildfire, but were essentially recovered by the end of the second season. Another wildfire in June 1963 burned a stand of Lehmann lovegrass (*Eragrostis lehmanniana*) that averaged 4,480 pounds per acre and a stand of black grama (*Bouteloua eriopoda*) that averaged about 2,200 pounds per acre. The fire killed nearly 98 percent of the lovegrass plants and most of the black grama plants. The lovegrass reseeded itself adequately within 4 months following the fire; the black grama recovered much more slowly.

Changes in shrub crown density and basal area density were observed for 5 years following a 1951 chaparral wildfire in the Pinal Mountains of central Arizona (Cable 1957). Five years following the burn, sprouting shrubs had regained a density that approximated shrub densities on unburned chaparral. However, no analysis was made of the ratio of living to dead material in the shrub crowns—an important consideration in evaluating the susceptibility of the chaparral stand to subsequent burning.

Southwestern Texas Grass-Shrub

No references available.

Fuel Types and Prescribed Fire

Ponderosa Pine

Three separate prescribed burning studies are in progress to investigate the effects of interval burning on fuel accumulation and consumption, fire intensity, vegetative and nutrient changes, stand structure, mortality and regeneration, and hydrologic properties of the soil and litter.[5]

The initial fuel reduction burn in the fall of 1976 on the Chimney Spring Unit (Fort Valley Experimental Forest, Ariz.) in a mature ponderosa pine stand reduced litter fuels from an average of 15 tons per acre to 5.5 tons per acre, a reduction of 63 percent. The woody fuels averaged 8.2 tons per acre prior to burning and 2.8 tons per acre following the fire for a 66 percent reduction. Fire history records indicated that there had been no fires on the area

[5] Unpublished office reports. On file with the Fuel Management Project, Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.

for about 100 years. The prescribed fire that accomplished the overall 64 percent fuel reduction can be characterized as a low intensity fire (15 to 120 Btu/sec/ft) that consumed a relatively small proportion of fuel in the fire front but continued to burn for many hours, consuming both litter and woody fuels in the process. This prolonged burning was a result of an extended period of moisture deficiency with corresponding low moisture contents of the ground fuels and large woody fuels.

The initial fuel reduction burn (fall 1977) on the Limestone Flats Unit (Long Valley Experimental Forest, Ariz.), also in mature ponderosa pine, reduced litter fuels from an average 15.6 tons per acre to 9.1 tons per acre—a reduction of 42 percent. The woody fuels on this area averaged 17.9 tons per acre before the fire and were reduced to 10 tons per acre following the fire for a 44 percent reduction. A detailed fire history has not been completed for the area but available fire scarred material indicates an historical fire interval of 3 to 5 years.

The prescribed fire that was applied to this area burned on 2 consecutive days but burning conditions on both days were nearly identical. Late season rainfall had increased the duff moisture content, had penetrated the exposed surfaces of the large fuels, and was largely responsible for the smaller amount of total fuel consumed (43 percent). Fuel moisture in the litter averaged about 7.5 percent; in the F layer, 9.5 percent; and in the H layer, about 26 percent. Fire intensities were calculated; they varied from about 10 to 15 Btu's per second per foot of fireline front for the backing fires to 100–120 Btu's per second per foot fireline intensity for short strip headfires.

On the San Juan National Forest in southern Colorado, prescribed burning is being applied to a predominantly young stand of ponderosa pine poles and sawtimber with a dense understory of Gambel oak (*Quercus gambelii*). The objectives of the study are to encourage natural regeneration, which has been largely absent for the past 60 years, reduce competition from Gambel oak, reduce fuel accumulations, and measure the effects of this seasonal, interval burning on nutrient cycling, grass and shrub succession, and cone production. Six 2.5-acre plots were burned in the fall of 1977. Litter fuels were reduced by 46 percent (from 15 to 7.4 tons/acre) and woody fuels were reduced by 49 percent (from 3.3 to 1.7 tons/acre). Duff depth was reduced from 2.1 to 0.57 inches—a reduction of 73 percent. The fire intensity on these plots was very low, varying from roughly 10 Btu's per second per foot for backing fires up to 100 Btu's per second per foot for the short strip headfires. Fuel inventory following the fire indicated that, while a small amount of sound material remained, virtually all of the large rotten material inventoried in the prefire survey was consumed.

In a prescribed fire study by Davis et al. (1968) and Ffolliott et al. (1977), two ¼-acre plots were burned to reduce the duff depth and encourage natural regeneration. The fire was described as a "moderately high intensity surface fire" having an average flame height of 2 feet. Estimated fireline intensities were 48 to 90 Btu's per second per foot—probably slightly high if flame lengths were only 2 feet. Generally, flame heights of about 2 feet are associated with fireline intensities of around 30 to 35 Btu's per second per foot. The fire on plot A consumed 70 percent of the duff depth but only 30 percent of the duff weight; the fire on plot B consumed 73 percent of the duff depth but, again, only 36 percent of the duff weight was consumed. Litter accumulation was measured for 2 years following the fires and reflects an abnormal rate of accumulation because of the presence of scorched needles falling along with natural needle fall. This information could not be used to represent normal annual accumulation of needle litter.

A study by Gaines et al. (1958) measured the effects of two prescribed fires on fuel consumption, timber stands, and surface vegetation but failed to provide any quantitative description of fire intensity. Weather conditions were described, and remarks indicated that the September fire was of much lower intensity than the October fire due to differences in relative humidity and air temperature. The September fire consumed 57 percent of the 17.29 tons of fuel per acre that was present before burning; the October fire, although described as being more intense, consumed only 15 percent of the 9.96 tons per acre of fuel available before the fire. This study included pre- and post-burn fuel weights for standing dead trees but the loading made up only a minor component of the total. One of the primary conclusions of the study was that trees and needles killed but not consumed by the fire added fuel to the area, partially offsetting the level of fuel reduction attributed to the two fires.

Unfortunately, a large number of good references that describe the use and effects of prescribed burning in southwestern ponderosa pine fail to include

any quantitative data on fuel loading and fuel consumption. When comments are made concerning fire intensity they have usually classified the levels by using such terms as "hot," "cool," "moderate," "light surface," "crown," etc. This is understandable since only recently have techniques become available to accurately inventory fuels and express the fuel loading and fire behavior in terms of intensity.

Some of the references that fit this category include work done by Weaver (1955, 1952), Morris and Mowat (1958), Lindenmuth (1962), and Biswell et al. (1973).

Mixed Conifer

No references available.

Pinyon-Juniper

No references available.

Chaparral

There is little available information concerning the use of prescribed burning in chaparral in the southwest that includes data on pre- and post-fire fuel loading and specific indicators of fire intensity. However, there are references that contain information on the effects of prescribed burning on various fuel components and imply changes in fuel loadings that result from prescribed burning. These are summarized below.

Pase and Lindenmuth (1971), reporting on four fall prescribed fires in Arizona chaparral, indicated that litter averaged 6.4 tons per acre before burning. An average of 34 percent of the litter (2.2 tons) was removed by fire during treatment of the four areas. Although no computations were made of shrub biomass, fuel consumption, or fire intensities, good records were kept of weather conditions and living and dead fuel moisture. Change in percent crown canopy cover was used as an indicator of shrub response following burning. At the end of the fifth growing season following the fire, shrub live oak had exceeded its pretreatment canopy cover. (*Author's note:* The percentage of dead to live crown material, however, must have remained very low.) The percent crown cover of all the shrubs and half shrubs (nine species), considered as a group, had returned to only 75 percent of the crown cover measured prior to burning. If percent crown cover could somehow be related to fuel loading in the various stands of chaparral, it would be possible to make fire intensity computations based on rate of spread and fuel consumed by the fire front.

In another study of litter production (in the absence of burning), Pase (1972) found that the total weight of accumulated litter varied from 9.2 to 27.1 tonnes per hectare and that there was a significant difference between litter accumulation on north and south slopes, with northerly aspects producing more litter than south slopes. A "crown volume index" (crown area × height) was used as an effective predictor of litter fall in shrub live oak stands, annual litter fall increasing approximately 0.1 kilogram for each cubic meter increase in shrub crown volume.

Pase and Glendening (1965) measured reduction of litter and shrub crown cover resulting from two prescribed burns in chaparral on the Sierra Ancha Experimental Forest near Globe, Ariz. No fire intensity factors were given but weather conditions recorded for the two fires indicated that one fire burned under conditions described as "moderate," the other under "more critical" conditions. The more intense fire reduced the litter by 51 percent and the shrub crown cover by 95 percent; the moderate fire resulted in a litter reduction of 29 percent and a reduction in shrub crown of 93 percent—only slightly lower than the more intense fire.

Pase and Knipe (1977), reporting on a chaparral watershed that was burned over by a wildfire in 1959, converted to grass through the use of chemicals and fire, and maintained in grass using prescribed fire, found that following a maintenance burn in 1971, herbage production increased on both north and south slopes above the preburn levels. There was ultimately a 41.4 percent increase in herbage production as a result of burning. Preburn levels were 1,125 pounds per acre on north slopes and 1,203 pounds per acre on south slopes. The watershed was burned in the winter when grasses were cured. No weather records were included other than rainfall amounts which indicated below normal moisture conditions for the area.

Prior to the above 1959 wildfire, shrub cover was 73 percent, consisting of shrub live oak and birchleaf mountain mahogany (*Cercocarpus betuloides*). The fire reduced the shrub cover to 5 percent. The prescribed fire in 1971 was applied in an effort to maintain the grass cover type and resulted in a topkill of 71 percent for shrub live oak and 68 percent for mountain mahogany, while increasing the herbage production in the area.

A chaparral conversion project, completed in 1965, on the Tonto National Forest, Ariz., was reported by Baldwin (1968). He estimated that fuel loadings in the mature chaparral stands involved in the conversion project totaled 30 to 50 tons per acre. There was no description of the fire that accomplished the conversion nor were there estimates made of the residual fuel following the fire. However, photographs of the area following the fire indicated that a large amount of standing brush remained. The 5,000-acre project was converted to grass and 200 head of cattle were placed on the area under a rotation system of management. Prior to the conversion, the area supported about 20 head of wild cattle on a year-long basis—an indication of the relatively small amount of forage available for grazing prior to conversion.

Semidesert Grass-Shrub

Cable (1967) reported on two June prescribed fires (1952 and 1955) on the Santa Rita Experimental Range near Tucson, Ariz. The objectives of the burning were to measure changes in grass and shrub cover (fuels) after burning in order to determine the effectiveness of prescribed burning for shrub control, and to determine the direct and indirect effects of burning on perennial grasses. Weather was documented for each burn and available ground fuels prior to burning totaled 300 pounds per acre on one fire and 600 pounds per acre on the other. Results indicated that both fires killed over 90 percent of the burroweed (*Haplopappus tenuisectus*) and nearly half the cactus plants. Production of perennial grasses apparently was not favored by burning but annual grasses increased significantly—probably as a result of the reduced competition from burroweed. The two fires were relatively ineffective for controlling mesquite.

Postfire fuel loadings were not available, but fires in this type tend to consume all the ground fuel and some portions of the standing shrubs, and create new dead woody material that may be consumed by a subsequent fire.

Pase (1971) reported that a "relatively cool" February prescribed fire in an established stand of Lehmann lovegrass in central Arizona killed less than 5 percent of the lovegrass plants. The stand contained 700 to 800 pounds per acre of lovegrass prior to treatment. Production on the area following burning was about 20 percent higher than on the control. A summary of burning conditions indicated 0.88 inches of rainfall on the area 4 days prior to burning; good soil moisture; light winds; 39-percent relative humidity; and air temperature of 65° F.

Cable (1972) indicated that prescribed fire can be used, when fuel is adequate, to reduce encroachment of shrubby species and prevent them from reaching seed-bearing size; that some perennial grasses respond very well to burning while others are less tolerant; and that, overall, prescribed burning will seldom increase perennial grass production in the southwestern semidesert, may reduce productivity temporarily, and will likely change the relative abundance of many of the species.

Southwestern Texas Grass-Shrub

Wright and Britton (1969) and Heirman and Wright (1970) report on a phenomenon they refer to as "burndown" in using prescribed fire on mesquite (*Prosopis* sp.) trees previously killed by aerial spraying in southwestern Texas. Burndown is influenced by fuel loading prior to the fire, wind velocity, air temperature, relative humidity, and tree size. A formula is presented that integrates these variables into a percentage figure that will tell the manager how much of the standing dead mesquite might be expected to burn as a result of his prescribed fire. Fuel loading is an important variable in mesquite stands where wood borer activity is present in the dead wood. A 30 percent burndown may be expected when there is 3,000 pounds of fuel per acre; a 70 percent burndown is possible with 5,000 pounds of fuel per acre. With less than 3,000 pounds fuel per acre little burndown may be expected regardless of wood borer activity in the dead wood.

Two prescribed burns were conducted in 1970 and 1971 near Baird, Tex., in ashe juniper (*Juniperus ashei*) communities (Wink and Wright 1972). The studies were to determine the effects of fire on yields of five dominant grasses, and to determine the amount of fine fuel needed to carry a fire to consume piled brush and kill young juniper trees. Spring of 1970 was wet; spring of 1971 was dry. The wet year produced an increased herbage yield for four of the five species (943 to 5,012 lb/acre); in the dry year only two grass species showed increases. The minimum amount of fine fuel necessary to carry a headfire was 1,000 pounds per acre. In areas where the fire carried, 99 percent of the piles were consumed and 99 percent of the juniper trees less than 6 feet tall were killed.

Wright (1972b) studied rate of litter buildup on tobosa-grass (*Hilaria mutica*) communities follow-

ing prescribed burning and found that reburns could be conducted at intervals of every 4 to 7 years because litter accumulation approached preburn conditions (4,000 lb/acre) in about 4 years.

A number of additional articles about this southwestern region of Texas summarize changes in plant productivity resulting from prescribed burning (Neuenschwander and Wright 1973a, 1973b, 1973c; Dahl and Goen 1973; Box 1968). These references generally emphasize those factors that are important to range managers, including: herbaceous fuel loading before the fire, changes in species and productivity following the fire, and the time-related effects of the fire. The reports generally leave the impression that most of the herbaceous fuel is consumed by the fire so computing a fire intensity might well be done using the figures for preburn fuel loading. For the most part, quantitative descriptions of fire intensity are not available. There are, however, some important implications in these references concerning fuel dynamics as a result of burning.

Finally, prescribed burning studies have been conducted by Wright (1968) in the vicinity of Colorado City, Tex., that attempt to (1) relate maximum temperatures at soil surface to quantity of grass fuel; (2) determine how mesquite responds to top removal in relation to season; and (3) determine the effects of spring burning on tobosa-grass. Fuels consumed ranged from 1,545 to 7,025 pounds per acre and corresponding maximum temperatures during the fire at the mineral soil surface varied from 182° to 1,260° F. Weather factors were monitored on each burn and fuel moisture measurements were made, but no attempt was made to compute fireline intensity values that could be related to soil temperature or effects on plants exposed to the fires. There appeared to be a good relationship between fuel loading and peak temperature at the soil surface. The relationships were consistently different between a rolling plains area and a high plains area where the burns were conducted. At one point, where there was 7,000 pounds of fuel per acre, the resulting maximum temperature at the soil surface reached 1,000°F.

Research Needs and Priorities

Wildfires

While additional information is needed, there is a considerable amount of data available concerning the effects of wildfires on fuels in ponderosa pine, chaparral, semidesert grass-shrub communities, and southwestern Texas semidesert plant communities. By contrast very little information is available on wildfire effects in mixed conifer and pinyon-juniper stands. Wildfires frequently convert these stands from a predominantly living to a predominantly dead condition, and in the case of mixed conifer stands, heavy fuel loadings of both down and standing material can be expected. In the pinyon-juniper type, wildfires appear to consume most of the ground fuels and the fuel that remains is in the form of standing dead trees killed by the fire. Few measurements have been made of these conversions, but compared with the need to measure the effects of prescribed fire on fuels, the priority could only be considered as medium.

Prescribed Fire

If prescribed burning is to be used more effectively as a land management practice in the Southwestern forest and cover types, more research is needed concerning the effects of burning on the fuel complex. Specifically, land managers must have available to them predictive tools that will tell, with a minimum of sampling, what fuel is on the area prior to burning, what fuel is consumed by the fire, what can be expected in the way of subsequent fuel accumulation, and what all this means in terms of achieving established fuel management goals and objectives.

The need for research relating to the effects of prescribed burning on fuels falls in two general categories:

1. The effects of single and multiple applications of prescribed fire on fire hazard, and
2. The effects of this application of fire on the fuels found in the various cover types of the Southwest where prescribed fire now has application or is being proposed for use.

Most of the research needs and priorities can be related specifically to the various timber or cover types where prescribed fire has application, or to types where it is yet to be determined if prescribed burning has a place in the management of the type. The following research needs are paramount (high priority) in gaining a better understanding of the effects of prescribed burning on fuels in southwestern forest and cover types.

- Continue to develop and refine initial fuel reduction burning prescriptions in ponderosa pine and mixed conifer natural fuels, which

will result in an acceptable level of fuel reduction and not cause unacceptable damage to the stand.

- Same as above except for activity-created fuels.
- Develop prescriptions for applying successive multiple or interval burns that will produce an acceptable level of fire intensity and at the same time prevent unacceptable levels of fuel accumulations between burns.
- Develop prescriptions that will permit fresh ponderosa pine slash to be safely and effectively broadcast burned without causing unacceptable damage to the residual stand.
- Develop the basic information needed to prepare guidelines that will permit the land manager to express his prescribed burning accomplishments in terms of the amounts of fuel consumed by various size classes, age, and types of combustible materials.
- Develop burning prescriptions for reducing excessive litter fuel loadings that will improve the seedbed conditions for natural regeneration, protect the soil, and prevent excessive runoff.

Central Rocky Mountains

Fuel Types and Fire Activity

In the search for available fuel information pertaining to the Central Rocky Mountains (Forest Service Region 2), Colorado (except southern portion), South Dakota, and the southern part of Wyoming were considered. Within this area, approximately 24.2 million acres of land are administered by the Forest Service, of which 22 million acres are National Forest land.

A 6-month period, May through October, constitutes the fire season. Over 90 percent of the fires and acres burned occurred during this 6-month period. June, July, and August account for over 65 percent of the fires. October is often a high fire danger period because of drying weather and herbaceous fuels being fully cured.

In regard to National Forest lands in Region 2, the percentages of the total number of fires caused by lightning and people are 59 and 41 percent, respectively (Barrows 1978). However, over 65 percent of the total fires are human-caused when considering all lands—Federal, State, and private. The increased use of Federal and State lands for outdoor-related activities by the general public poses a special fire management problem in areas of Region 2 near high population centers.

In general, prescribed burning is conducted from mid-March through May and from September until mid-November; however, this is dependent on the management and/or research objectives set forth for each prescribed burn.

Information regarding fire effects on fuels is very limited for the Central Rocky Mountains. The available information has been summarized by cover types within the following categories: (1) wildfires, (2) prescribed fires, and (3) status-of-fuel inventory data.

Within the above categories, available fuel information was summarized using the following SAF general cover types:

Fuel type	*SAF Cover Type*
Grass-shrub communities	
Pinyon-juniper (*Pinus edulis* and *Juniperus scopulorum*)	239
Ponderosa pine (*Pinus ponderosa*)	.237
Mixed conifer (ponderosa pine and Douglas-fir)	214
Douglas-fir (*Pseudotsuga menziesii*)	210
Lodgepole pine (*Pinus contorta*)	218
Quaking aspen (*Populus tremuloides*)	217
Engelman spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*)	206

Wildfire

Currently, quantitative fuel data are not available for wildfire situations in the Central Rocky Mountains.

Prescribed Fire

Grass-Shrub

No references available.

Pinyon-Juniper

No references available.

Ponderosa Pine

A research project at Colorado State University titled, "The Role of Fire in Ponderosa Pine-Mixed Conifer Ecosystems," has collected and compiled information on pre- and post-fire fuel inventories and fire behavior for two prescribed fires in Rocky Mountain National Park (Rowdabaugh 1978). A fire history was developed for the area and fire effects information on the vegetation complex, soil nutrient levels, and mountain pine beetle infestations has also been collected and analyzed. A brief description and summary tables of the fire environment, including pre- and post-fire fuel inventories, and fire behavior are presented for the Eagles Cliff and Mill Creek prescribed fires.

Eagles Cliff (35 acres).—The cover is characterized by a ponderosa pine overstory heavily infested with mountain pine beetles and a bitterbrush-bunchgrass understory. Stand age is approximately 300 years. The site is located at an elevation of 8,400 feet with a south-southeast aspect. Slopes range from 10 to 52 percent. The soil is a shallow sandy loam type. Dominant fuel types are: (1) slash resulting from pine beetle control activities, (2) bitterbrush-bunchgrass, and (3) litter and duff.

Downed woody fuels, herbaceous vegetation, and litter and duff fuels were inventoried before and after burning. Fire behavior descriptors measured were rate of spread, flame length (fireline intensity estimated using flame length data), residence time, and total heat released. Weather variables were measured on site and fuel moisture samples were collected and ovendried to determine fuel moistures by time lag classes.

Tables 1 to 3 summarize fire behavior and pre- and post-fire fuel loadings pertaining to the Eagles Cliff prescribed burn.

Fuel consumption for the slash fuel plots averaged 70.3 percent and 69.2 percent for the non-slash fuel plots. The fire consumed 100 percent of the woody material on the ground below 3 inches in diameter. Fuel consumption for the downed woody material greater-than-3-inch size class was approximately 43.7 percent. Varying amounts of litter, duff, and herbaceous vegetation (live and dead) were consumed.

Non-slash fuels did not experience this same degree of fuel consumption. The average amount of fuel consumed in the 0.0 to 0.24, 0.25 to 0.99, 1.0 to 2.99, and greater than 3.0 inch size classes of downed woody material was 75.8, 89.8, 100.0, and 100.0 percent, respectively. Approximately 88 percent of the litter loading and 61 percent of the duff loading were consumed. Herbaceous vegetation (live and dead) experienced 96 percent consumption.

On the slash fuel plots, herbaceous vegetation increased 500 percent over the prefire condition. However, herbaceous vegetation increased to only 73.6 percent of the prefire condition on nonslash plots.

Mill Creek (2 acres).—This burn area is characterized by a mountain pine beetle-infested ponderosa pine overstory with a bitterbrush-big sagebrush-bunchgrass understory. Grass-shrub is the dominant fuel type. The site is located at an elevation of 7,900 feet with a south-southwest aspect. Slopes ranged from 3 to 32 percent. The dominant fuel types are: (1) shrub-bunchgrass-litter, and (2) bunchgrass-litter. Downed woody material was not a major factor in fire spread compared to grass and shrubs.

Downed woody material, herbaceous vegetation, litter, duff, and shrub fuels were inventoried before and after burning. Fire behavior descriptors measured were rate of spread, flame length (fireline intensity is estimated from flame length data), residence time, and total heat released. Techniques used for measuring fuel moistures were similar to those described earlier for Eagles Cliff.

Tables 4 to 7 summarize fire behavior and pre- and post-fire fuel loadings of the Mill Creek burn.

The degree of fuel consumption for the 0.0–0.24, 0.25–0.99, and 1.0–2.99 inch downed woody materials were 24.5, 54.4, and 50.0 percent, respectively. Litter consumption was 83.3 percent, while only 43.8 percent of the duff loading was removed. Herbaceous vegetation increased 103.1 percent over its initial prefire condition 1 year after burning.

Another research project at Colorado State University is being conducted in conjunction with the Colorado Division of Wildlife Big Horn Sheep Habitat Study Project and the Araphoe-Roosevelt National Forest. This project is to evaluate the effects of prescribed burning on big horn sheep (*Ovis*

Table 1.—*Fuel loadings and fire behavior descriptors of the Eagles Cliff prescribed fire (approximately 35 acres)*

Plot number	Fuel loading		Fire behavior descriptors			
	Prefire fuel load	Fuel consumed	Linear rate of spread	Flame length	Byram's Intensity	Total heat release
	Tons/acre	*Tons/acre*	*Feet/minute*	*Feet*	*Btu/fireline foot second*	*Btu/square feet*
3	6.6586	4.4123	14.2	8.5	594.8	1,700.1
[1]11	67.7897	45.5090	11.5	25.5	6,479.8	17,604.5
[1]19	72.8171	40.6225	13.8	15.6	2,226.5	15,521.2
20	13.1138	13.0908	4.5	2.5	41.6	4,837.0
26	18.2360	17.2557	4.9	4.5	149.2	6,384.6
27	15.9094	6.0459	7.0	6.5	332.0	2,267.4
28	5.8248	5.2222	16.7	12.2	1,304.7	2,001.7
[1]30	71.2161	53.5013	31.0	27.1	7,396.3	20,346.0
32	5.7650	4.4701	3.6	2.0	25.6	1,715.5
33	9.5301	8.1936	14.7	7.2	414.6	3,057.6
34	35.8952	34.8773	12.3	8.7	625.6	12,912.9
35	18.9024	15.4735	8.9	4.4	142.1	5,725.1
40	25.3589	15.1316	4.1	2.5	41.6	5,636.7
42	7,4843	1.0348	1.5	1.0	5.7	382.0

[1] Denotes slash fuels.

Table 2.—*Prefire fuel loading by ground and surface fuel components of the Eagles Cliff prescribed fire site*

Plot number	Loading by ground and surface fuel component									
	Downed woody size classes (diameter in inches)					Forest floor		Herbaceous vegetation		Total fuel loading
	0–0.24	0.25–0.99	1.0–2.99	3.0+ (sound)	3.0 (rotten)	Litter	Duff	Live	Dead	
	Tons/acre									
3	0.2596	1.3145	[1]—	—	—	0.5286	4.4467	0.0022	0.1070	6.6586
[2]11	.2144	10.7598	11.9315	37.1404	—	1.2721	6.2253	.0050	.2414	67.7897
[2]12	.0614	1.9625	1.7099	15.7023	—	1.9924	4.4467	.0011	.0535	25.9298
14	.0705	—	—	—	—	.4419	3.1127	.0072	.3513	3.9836
16	.0467	—	—	—	—	.6809	18.2313	.0096	.4697	19.4382
[2]19	.2731	6.7855	6.7567	47.0254	1.3112	2.5950	8.0040	.0013	.0649	72.8171
20	.0461	.1604	—	—	—	.6397	12.0060	.0052	.2564	13.1138
21	.0230	.4795	—	—	—	.0636	.4447	.0207	1.0135	2.0450
22	—	.1589	—	—	—	.2674	3.5573	.0203	.9950	4.9989
26	.1365	—	—	—	—	1.3075	16.4527	.0068	.3325	18.2360
27	.2729	.3168	—	—	—	.6551	13.7847	.0176	.8623	15.9094
28	.0454	—	—	—	—	.6831	4.8913	.0041	.2009	5.8248
29	.0223	1.3986	—	—	—	1.3870	21.7887	.0048	.2364	24.8378
[2]30	.3026	13.5324	4.2109	27.4719	—	.7534	24.9014	.0075	.0360	71.2161
32	.1159	.4843	—	—	—	.9032	4.0020	.0052	.2544	5.7650
33	.1623	.6457	—	—	—	.9032	7.5593	.0052	.2544	9.5301
34	.0921	.6415	1.1678	—	—	1.0332	32.9053	.0011	.0542	35.8952
35	.0467	—	—	1.2339	—	2.3317	15.1187	.0034	.1680	18.9024
40	.1790	.3116	—	—	—	1.6989	23.1227	.0009	.0458	25.3589
41	.1990	.1540	1.1214	16.1275	—	1.2562	13.7847	.0002	.0102	32.6532
42	.0217	—	—	—	—	.2213	7.1147	.0026	.1240	7.4843
43	.0223	.1620	—	—	—	.3292	2.6680	.0041	.2002	3.3858
44	—	.3286	—	—	—	.9083	3.1127	.0036	.1748	4.5280

[1] Dashes mean that samples or data are unavailable for that category.
[2] Denotes slash fuels.

Table 3.—*Post-fire fuel loading by ground and surface fuel components of the Eagles Cliff prescribed fire site*

Plot number	Loading by ground and surface fuel component									
	Downed woody size classes (diameter in inches)					Forest floor		Herbaceous vegetation		Total fuel loading
	0–0.24	0.25–0.99	1.0–2.99	3.0+ (sound)	3.0+ (rotten)	Litter	Duff	Live	Dead	
	Tons/acre									
3	0.0236	[1]—	—	—	—	—	2.2233	—	—	2.2463
[2]11	—	—	—	22.2807	—	—	—	—	—	22.2807
[2]12	—	—	—	5.0926	—	—	—	—	—	5.0926
14	.0235	—	—	—	—	0.0674	.8893	0.0001	0.0016	.9819
16	—	—	—	—	—	—	—	—	—	—
[2]19	—	—	—	32.1946	—	—	—	—	—	32.1946
20	.0230	—	—	—	—	—	—	—	—	.0230
21	.0230	—	—	—	—	—	.8893	—	—	.9123
22	.0228	—	—	—	—	—	1.7787	—	—	1.8015
26	.0910	—	—	—	—	—	.8893	—	—	.9803
27	—	—	—	—	—	.0808	9.7827	—	—	9.8635
28	—	0.1579	—	—	—	—	.4447	—	—	.6026
29	—	—	1.1316	—	—	—	16.0080	—	—	17.1396
[2]30	—	—	—	17.7148	—	—	—	—	—	17.7148
32	—	.1614	—	—	—	.1282	.8893	.0007	.0362	1.2949
33	—	.3229	—	—	—	.1042	.8893	.0004	.0197	1.3365
34	—	—	—	—	—	.1265	.8893	.0001	.0020	1.0179
35	—	—	—	—	—	1.1717	2.2233	.0007	.0332	3.4289
40	—	—	—	—	—	—	10.2273	—	—	10.2273
41	—	—	—	—	—	.4406	7.3370	—	—	7.7776
42	.0217	—	—	—	—	.1649	6.2253	.0008	.0368	6.4495
43	—	—	—	—	—	—	1.2932	—	—	1.2932
44	.0236	.1643	—	—	—	—	2.2233	—	—	2.4112

[1] Dashes mean that samples or data are unavailable for that category.
[2] Denotes slash fuels.

Table 4.—*Fuel loadings and fire behavior descriptors of the Mill Creek prescribed fire (approximately 2 acres)*

Plot number	Fuel loading		Fire behavior descriptors			
	Prefire fuel load	Fuel consumed	Linear rate of spread	Flame length	Byram's Intensity	Total heat release
	Tons/acre		*Feet/minute*	*Feet*	*Btu/fireline foot/second*	*Btu/square foot*
1	16.3461	11.2120	7.4	4.4	142.1	3,014.9
2	4.5156	[1]—	15.5	4.5	149.2	342.1
3	8.8457	2.0087	5.5	2.5	41.6	855.2
4	9.9809	3.1496	3.3	2.5	28.5	1,242.3136
5	11.0608	9.6320	7.7	4.6	156.5	3,567.9
6	18.6218	15.7183	7.2	4.8	171.7	5,835.1

[1] Data are not available.

canadensis) habitat. Several prescribed burns are proposed for the fall of 1978. The cover type at Wintersteen Park, site of the burning project, is an old growth ponderosa pine overstory with a shrub-bunchgrass understory. Three distinct fuel types dominate the area:

(1) Decadent ponderosa pine overstory and a heterogeneous understory of bunchgrass species, big sagebrush, and fine woody material constitutes the surface fuel component. Ground fuel component is primary pine needle litter.

(2) Homogeneous surface fuel component of big sagebrush intermixed with bunchgrass species. Ground fuel component is herbaceous material and shrub leaf litter.

(3) Homogeneous surface fuel component dominated by bunchgrass species with isolated clumps of big sagebrush. Ground fuel component consists mainly of herbaceous litter.

Pre- and post-fire inventories of fuels, vegetation, soils, and wildlife habitat will be collected and analyzed. Weather variables and fire behavior data will be measured during the burning period. Table 8 summarizes the prefire fuel loadings for the study area.[6]

The Black Hills National Forest in South Dakota is presently compiling pre- and post-fire fuel data for several prescribed burns in ponderosa pine stands. As of this date, none of the information is available.

[6] Unpublished report on file with the Fire Science Program at Colorado State University, Fort Collins, Colo.

No references are available concerning prescribed fire effects on fuels for the following cover types: (d) mixed conifer, (e) Douglas-fir, (f) lodgepole pine, (g) quaking aspen, and (h) Englemann spruce and subalpine fir.

Research Needs and Priorities

Available information on the effects of both wildfires and prescribed fires on fuels in the Central Rocky Mountains is lacking in several areas. There have been no studies that have attempted to describe the fuel changes resulting from wildfires in any of the cover types listed. Only recently have there been studies on the effects of prescribed fire on fuels, and these have been limited to the ponderosa pine type where prescribed burning shows the most promise for use and application. These studies are of high priority and should be continued.

Of moderate priority would be studies in the use of prescribed fire for reducing fuels in lodgepole pine and for regenerating decadent aspen stands. Use of fire for these purposes has not been tested but the prospects for success appear favorable and studies should be conducted to determine both the effects and feasibility of such use.

Fire has had only limited use in treating fuels in mixed conifer, Douglas-fir, and Englemann spruce-subalpine fir types. If fire has been used at all, it has been in treating clearcut blocks or in disposing of material that has been machine or hand piled. It appears that broadcast burning, with the possible exception of burning in the clearcut blocks, has very limited application in these types. Hence, priorities for research in this use would be considered low in relation to other research needs.

Table 5.—*Fuel loading by ground and surface fuel components of the Mill Creek prescribed fire site*

Plot number	Loading by ground and surface fuel component									
	Downed woody size classes					Forest floor		Herbaceous vegetation		Total fuel loading[1]
	0–0.24"	0.25–0.99"	1.0–2.99"	3.0"+ (sound)	3.0"+ (rotten)	Litter	Duff	Live	Dead	
	Tons/acre									
Prefire										
1	0.3246	1.0547	1.0972	—[2]	—	2.3170	6.2253	0.0136	0.0355	16.3461
2	.1080	1.0529	1.0953	—	—	.6742	1.3340	.0283	.1445	4.5156
3	.5758	1.1226	.5838	—	—	.1777	1.5563	.0872	.0889	8.8457
4	.0220	.4593	—	—	—	.7406	1.7787	.0366	.0468	9.9809
5	.2848	.3051	.5555	—	—	.4105	8.8933	.0517	.0661	11.0608
6	.1946	.9031	—	—	—	.7886	6.6700	.0573	.0950	18.6218
Postfire										
1	.2813	.1507	—	—	—	—	—	—	—	5.1341
2	.1080	1.0529	1.0953	—	—	.6742	1.3340	.0283	.1445	5.3346
3	.3685	.4811	—	—	—	—	1.3340	—	—	6.8370
4	.1319	.4593	—	—	—	—	1.1858	—	—	6.8313
5	.1972	—	.5555	—	—	—	.5929	—	—	1.4288
6	.0649	.1505	—	—	—	—	1.6304	—	—	2.9035
1st year postfire										
1	.1298	1.5067	—	—	.6302	.6563	3.1127	.0327	.0008	10.7713
2	.4104	2.5569	1.6429	—	—	.9011	1.7787	.1360	.0114	8.3348
3	.5067	.8018	1.7516	—	—	.4092	3.7797	.3013	.0163	12.2200
4	.2199	1.9185	—	—	—	.3196	2.4457	.0371	.0010	8.9961
5	.3067	1.9833	—	—	—	.5492	2.6680	.0833	.0070	5.6807
6	.1946	1.5052	.5480	—	—	.4544	3.1127	.1217	.0256	7.0199

[1] Shrub loading included in total loading.
[2] Dashes indicate none of fuel component present.

Table 6.—*Prefire fuel loading contributed by shrub components of the Mill Creek prescribed fire site*

Plot number	Species	Category	Total leaf weight	Total branchwood weight 0–0.50 cm	Total branchwood weight 0.51–2.00 cm	Total branchwood weight 2.01 cm+	Total aboveground weight
			Tons/acre				
1	Bitterbush	dead	—[1]	0.2635	0.3242	0.1650	0.7527
	(*Purshia tridentata*)	live	0.7556	1.3293	1.7337	.7319	4.5255
2	Bitterbush	dead	—	—	—	—	—
		live	.0164	.0437	.0184	—	.0784
3	Bitterbush	dead	—	.0975	.1025	.0658	.2658
		live	.4773	1.4335	1.5299	.9469	4.3876
4	Big sagebrush	dead	—	.3587	.4436	.1783	.9806
		live	.7778	1.8794	2.2490	1.0103	5.9164
5	Bitterbush	dead	—	.0446	.0387	—	.0833
		live	.0779	.1781	.1548	—	.4106
6	Bitterbush	dead	—	—	—	—	—
		live	1.1274	3.2478	3.7511	1.7870	9.9132

[1] Dashes indicate data are not available.

Table 7.—*Postfire fuel loading contributed by shrub components of the Mill Creek prescribed fire site*

Plot number	Species	Category	Total leaf weight	Total branchwood weight 0–0.50 cm	Total branchwood weight 0.51–2.00 cm	Total branchwood weight 2.01 cm +	Total aboveground weight
			Tons/acre				
1	Bitterbush	dead	—[1]	0.7541	0.9829	0.3173	2.0543
		live	0.4535	.8086	1.1006	.2852	2.6478
2	Bitterbush	dead	—	.3342	.4147	.1487	.8974
		live	—	—	—	—	—
3	Bitterbush	dead	—	.0975	.1025	.0658	.2658
		live	.4773	1.4335	1.5299	.9469	4.3876
4	Big sagebrush	dead	—	1.3807	1.5088	.8172	3.7070
		live	.2074	.4426	.6807	.0167	1.3473
5	Bitterbrush	dead	—	.0075	.0065	—	.0140
		live	.0133	.0299	.0261	—	.0692
6	Bitterbrush	dead	—	.0180	.0269	—	.0449
		live	.1599	.3423	.5107	—	1.0128

[1] Dashes indicate data are not available.

Intermountain States

Fuel Types and Fire Activity

The Intermountain area contains a wide variety of vegetative communities ranging from semi-desert grasslands to subalpine fir-spruce forests. Within the categories of forests and slash for the fuel group of conifer forests, there is a series of forest cover types that exist along an increasing elevation/latitude gradient. As elevation and/or latitude increases, fuel types change in the following order:

Fuel type	*SAF cover type*
Ponderosa pine	237
Douglas fir	210
Western white pine (*Pinus monticola*)	215
Larch-Douglas fir	212
Lodgepole pine	218
Engelmann spruce-subalpine fir	206

Both wildfires and prescribed fires are governed by variables that are established by the climate,

Table 8.—*Prefire fuel loading contributed by ground and surface fuel components of the Wintersteen Park prescribed burning site*

Fuel type	Average planar slope	Loading by ground and surface fuel components								
		Downed woody size classes					Forest floor	Herbaceous vegetation		Total[1] fuel loading
		0.0–0.24"	0.25–0.99"	1.0–2.99"	3.0"+ (sound)	3.0"+ (rotten)	Litter	Live	Dead	
	Percent	*Tons/acre*								
Ponderosa pine	35.0	0.1593	0.1696	0.2362	0.3041	0.2023	0.4638	0.1013	0.2362	6.2386
Shrub	18.3	.2575	.6666	.7787	—[2]	—	.4877	.1017	.2372	8.9589
Bunchgrass	9.2	.0869	.1506	.0548	—	—	.2905	.1297	.3026	3.2628

1 Includes loading contributed by shrub components.
2 No data available.

vegetation, topography, and weather at the time of burn. Three fire climate regions encompass the area (Schroeder and Buck 1970), although two have similar fire seasons. The Great Basin and the Northern Rocky Mountains have a fire season that usually extends from June through September; fuels progressively dry during this period. East of the Rockies in the northern Great Plains region, the fire season lasts from April through October, with the fire danger less severe in the summer months because of high humidity.

Fire effects (such as crown scorch, bark scorch, and cambium kill, root crown, and sprout kill), along with the amount of duff removed, can result in either dead and down woody material or standing snags, which in turn become fuel for a subsequent fire. This occurrence was discussed by Wellner (1970) and he pointed out that prior to about 1940, wildfire shaped the character of Northern Rocky Mountain forests more than any other single factor, except possibly precipitation. In addition, he pointed out, fire has been the primary factor responsible for the even-aged and young size classes. Surface fires tend to kill young trees of all species and mid-season high intensity wildfires generally kill all the trees. However, fires of less intensity burn out or kill species according to their ability to survive fire.

Flint (1925) rated the fire-resistance of the major species in the Northern Rocky Mountains and Wellner (1970) republished the rating with a supplement of the fire damage by ecosystem (tables 9 and 10).

Larsen (1925, 1929) discussed the effect of forest fires on vegetation in northern Idaho. His information on regeneration and succession following fire can be useful in estimating fuel loads even though he did not record or discuss fuels directly.

These tables indicate what portions of the stand become fuels for a fire or will be fuel for a subsequent fire. The bark, the branching characteristics, and the nature of the foliage all contribute to whether the stand will be totally involved or a less intense fire will be developed. Critical for any fire is the amount of dead and down material along with litter and duff available to burn during a stand's successional life. Information is limited for general use or highly developed for a specific area.

Analysis of inventory data collected on the St. Joe and Bitterroot National Forests shows an average dead and down total load of about 25 tons per acre. Initial analysis of inventory data from eight National Forests in Montana, Idaho, North Dakota, and South Dakota, by general habitat type, indicates the following total load variation.

Habitat Type	*Average total dead fuel load* (tons/acre)
No. 1. Ponderosa pine growing on ponderosa pine habitat sites	Less than 8
No. 2. Ponderosa pine growing on Douglas-fir habitat sites	Less than 12
No. 3. Douglas-fir growing on Douglas-fir habitat sites	Less than 20
No. 4. Lodgepole pine growing on fir-spruce habitat sites	Less than 20
No. 5. Fir and spruce growing on subalpine fir habitat sites	Less than 32
No. 6. Fir and hemlock growing on grand fir-hemlock habitat sites	Less than 27

The quantity of material less than 1 inch in diameter varied from about 1 ton per acre on the pine sites to 2.5 tons per acre on the cool, moist sites of spruce, fir, and hemlock. Although the cool, moist sites have higher amounts of fuels, the environment limits the probability of wildfire. Prescribed fire can be used effectively to reduce fuels and prepare the sites for silvicultural treatments.

An example of highly developed fuel information for a limited area is the work by Kessel (1976 a and b) for Glacier National Park. The distribution of fuels at various times after fire was investigated and reported for the same area by Jeske and Bevins (1976). The total fuel load, including shrub foliage and branchwood, went from 43 tonnes per hectare at 10 years since burn to a minumum of 19 tonnes per hectare at 105 years and then increased to over 44 tonnes per hectare at over 155 years after burn. High loads at 10 years were probably due to snag fall and the increase after 105 years could be accounted for by mortality becoming significant. Comparison of mesic and xeric sites showed the mesic sites producing about 0.1 tonnes per hectare

Table 9.—*Relative fire resistance of the more silviculturally important northern Rocky Mountain conifers*[1]

Species	Thickness of bark of old trees	Root habit	Resin in old bark	Tolerance: Branch habit	Tolerance: Stand habit	Relative flammability of foliage	Lichen growth	Degree of fire resistance
Western larch (*Larix occidentalis*)	Very thick	Deep	Very little	High and very open	Open	Low	Medium heavy	Most resistant
Ponderosa pine	Very thick	Deep	Abundant	Moderately high and open	Open	Medium	Medium to light	Very resistant
Douglas-fir	Very thick	Deep	Moderate	Moderately low and dense	Moderate to dense	High	Heavy to medium	Very resistant
Grand fir (*Abies grandis*)	Thick	Shallow	Very little	Low and dense	Dense	High	Heavy	Medium
Lodgepole pine	Very thin	Deep	Abundant	Moderately high and open	Open	Medium	Light	Medium
Western white pine	Medium	Medium	Abundant	High and dense	Dense	Medium	Heavy	Medium
Western redcedar (*Thuja plicata*)	Thin	Shallow	Very little	Moderately low and dense	Dense	High	Heavy	Medium
Engelmann spruce (*Tsuga mertensiana*)	Thin	Shallow	Moderate	Low and dense	Dense	Medium	Heavy	Low
Mountain hemlock (*Tsuga heterophylla*)	Medium	Medium	Very little	Low and dense	Dense	High	Medium to heavy	Low
Western hemlock	Medium	Shallow	Very little	Low and dense	Dense	High	Heavy	Low
Subalpine fir	Very thin	Shallow	Moderate	Very low and dense	Moderate to dense	High	Medum to heavy	Very low

[1] From Flint (1925).

per year more fuel than the xeric sites. The majority of this increase occurred in the large fuel size classes (greater than 3-inch diameter) and composed 53 of a total of 60 tonnes per hectare at more than 155 years after the fire. Three patterns of fuel distribution over time were observed: Fuels that decrease (grasses, herbs, and shrubs), those that plateau in a characteristic loading range (litter and 1- and 10-hour time lag fuels), and those that increase over time (greater than 100-hour time lag fuels).

Most investigations of wildfire describe fuel load after disturbance but few cases are available where prefire and postfire measurements of fuel quantity were made. Some inferences have been made and the probable fire effect on fuels documented.

Wildfire in severe fire weather will crown out in a forest, consuming the foliage and material less than ⅛-inch diameter; the shrub and regeneration less than ¼-inch diameter; and at least 20 percent of the duff, litter, and dead and down woody material in the fire front (Anderson 1968). Even greater amounts are consumed where fuel load, arrangement, and moisture content along with slope and wind are optimized.

Fire effects on forest cover types is varied according to climate and topography location. The frequency of fire affects the severity of fire in that less fuel buildup of material greater than 3 inches occurs on short fire cycles than on long cycles. Fire frequency increases from moist to dry sites and high to low elevations. The general fire considerations for the previously mentioned major forest cover types are described below:

Table 10.—*Estimated fire damage in major ecosystems of northern Rocky Mountain forests*

Ecosystem[1] (climax species)	Seral species[1] (varies by habitat type)	Fire damage (varies by fire intensity)	Surviving species (varies by fire intensity)
Ponderosa pine	None	Slight to extreme—usually moderate	Ponderosa pine
Douglas-fir	Ponderosa pine Lodgepole pine Western larch	Slight to complete—usually extreme	Western larch Ponderosa pine Douglas-fir Lodgepole pine
Grand fir	Ponderosa pine Douglas-fir Western larch Lodgepole pine Western white pine Engelmann spruce	Moderate to complete—usually extreme	Western larch Ponderosa pine Douglas-fir Western white pine Lodgepole pine
Western redcedar (western hemlock)	Douglas-fir Western larch Lodgepole pine Grand fir Western white pine Engelmann spruce	Moderate to complete—usually extreme	Western larch Douglas-fir Grand fir Western white pine Western redcedar
Western hemlock	Douglas-fir Western larch	Moderate to complete—usually extreme	Western larch, Douglas-fir
Subalpine fir (Engelmann spruce)	Douglas-fir Western larch Lodgepole pine Western white pine Engelmann spruce	Extreme to complete—usually extreme	Western larch Douglas-fir
Mountain hemlock (subalpine fir)	Western larch Lodgepole pine Western white pine Engelmann spruce Whitebark pine	Extreme to complete—usually extreme	Western larch

[1] From Daubenmire and Daubenmire (1968) with modifications.

Ponderosa Pine

This type exists as the lowest and most drought resistant timber type, appearing just above the grass-sagebrush zone and below the appearance of interior Douglas-fir. Because of features noted in Table 9, this species serves as a recorder of fire frequency from bole fire scars (Arno 1976).

The mean firefree intervals found by Arno ranged from 6 to 11 years, depending upon location, with intervals as high as 20 years. Fuel loadings are generally light as indicated by the inventory of total fuel in a ponderosa pine-fescue habitat type with a load of 3 tons per acre.[7] The very dry sites appear to perpetuate pine without routine fire occurrence because of the severe xeric conditions. As in other regions of the country, fire contributes to maintaining ponderosa pine on the site and helps establish seedbeds (Biswell et al. 1973). Litter fuel loads have been found to range from 2.7 to 0.6 tons per acre in western Montana, with an average of 1.4 tons per acre. The total forest floor fuel load averaged 11.7 tons per acre (Brown 1970). Research in the Selway-Bitterroot Wilderness by Habeck (1974) shows a fuel loading of 3.9 tons per acre on the warm dry sites occupied by ponderosa pine. Data on distribution by size class are given, but data on changes over time are limited or nonexistent for other geographical sites.

The amount of live fuel contributed by the tree crown in foliage and branchwood less than 3 inches has been investigated by Brown (1978) for the major species of the Intermountain area. For ponderosa pine trees greater than 1 inch, the total weight is estimated by:

$$W = EXP\ 0.2680 + (2.0740\ (lnd\ d))$$

Where d is the d.b.h. in inches and is valid from 1- to 34-inch d.b.h. This general equation form is used for nine species of this area (see table 11). For three

[7] Aldrich, D. F., and R. W. Mutch. 1972. Ecological interpretations of the White Cap Drainage: A basis for wilderness fire management. 109 p. Review draft on file at the Intermountain Forest and Range Experiment Station, Ogden, Utah.

Table 11.—*Equation forms to predict crown weights per tree of material less than 3 inches for 11 species of the Intermountain west (from Brown 1978)*

$W = a + b\,(\ln d)$

Species	a	b	Range of d.b.h.	Weight at 8 in. d.b.h.
			Inch	*Pounds*
Western larch	0.4373	1.6786	1–35	51
Western white pine	.7276	1.5497	1–43	52
Lodgepole pine	.1224	1.8820	1–16	57
Western hemlock	.7218	1.7502	1–32	78
Interior Douglas-fir	1.1368	1.5819	1–17	84
Ponderosa pine	.2680	2.0740	1–34	98
Western redcedar	.8815	1.6389	1–37	99
Spruce	1.0404	1.7096	1–29	99
Grand fir	1.3094	1.6076	1–40	105
For species not fitting the above, the equation form becomes $w = a + b\,(d^2)$				
Whitebark pine (*Pinus albicaulis*)	−1.000	.8371	1–8	53
Alpine fir	7.345	1.2550	1–13	88
Interior Douglas-fir	−20.740	1.0237	17–34	[1]—

[1] No data.

other species (table 11), another equation form best fits the data:

$$W = a + b(d^2)$$

The coefficients and range of diameters investigated are given in table 11. The proportion of the total fuel quantity in foliage, less than 0.25-inch material, 0.25- to 1.0-inch material, and 1.0- to 3.0-inch material can be estimated from equations presented by Brown (1978). The fuel consumed by crown fire or prescribed fire can be estimated from this information.

Ponderosa Pine—Rocky Mountain Douglas-fir

In the northern Rocky Mountains just above the ponderosa pine zone and below the Engelmann spruce-subalpine fir zone, there is a mid-elevation zone characterized by the presence of Douglas-fir. These forests cover about 20 million acres in Montana, Idaho, and northeastern Washington. Habeck and Mutch (1973) note that ponderosa pine is a major seral species on the warmer, drier aspects, while western larch is found on the cooler, more mesic northern aspects. All three of these species tend to survive low to moderate fires because of their thick bark. Fire frequency may average from 7 to 19 years, depending on location (Arno 1976), but it ranges from between 2 to 50 years, which agrees with findings by Aldrich and Mutch.[8] Aldrich and Mutch indicate that the biomass productivity is relatively good, and light fires could be supported annually. As fire frequency intervals indicate above, enough small fuels accumulate between fires so that fire intensity can be high enough in the regeneration stand to pose a crown fire potential. The total fuel load found by Habeck (1974) on cool, mesic sites with duff depths under 1 centimeter was 4.2 tons per acre. Sites which had not experienced fire and had duff depths greater than 0.4 inches had total fuel loads of from 20.6 to 36.7 tons per acre depending on the site. Only limited information is available on the range of fuel loadings by size classes as a function of time or other physical gradients.

[8] See footnote 6.

Western White Pine

Wellner (1973), reporting on silviculture systems for western white pine forests, noted that fire has maintained western white pine, western larch, and lodgepole pine in the Northern Rocky Mountains. Even-aged stands are usually the result of this, and succession shifts from mixtures of many species to climax forests of few species. Annual litter fall has been reported at about 0.60 ton per acre, (USDA 1965). The type occurs in the same zone as interior Douglas-fir and occurs with many of the same associate species. It is considered a fire-climax type with fire frequency being less than indicated for ponderosa pine or Douglas-fir, probably 50 to 100 years. When fire does occur, it is usually an intense fire that consumes most ground fuel and kills the overstory, thereby leading to an even-aged forest.

Preliminary examination of fuel inventory data of dead and down woody material for 48 stands indicated an average load of 23.4 tons per acre. The distribution of fuel load by size class was:

Size Class	0.25–1.0 inch	1.0–3.0 inches	3+ sound inches	3+ rotten inches	Total
			Tons/acre		
Average load	1.28	1.96	7.40	12.76	23.40
Maximum load	3.60	8.60	66.50	62.30	141.00

Few additional data are available, but fuel appraisal activities are developing useful information.

Western larch–Interior Douglas-fir

This type occupies 3½ million acres, mainly in the Northern Rocky Mountains, but is found in the moist region of northern Washington, Idaho, and Montana. This type often originates after fire, but tends to remain rather stable. It is fire resistant, seeds quickly to reestablish, and develops a high, light crown not conducive to crown fires. Fire frequency is probably closely tied to that associated with interior Douglas-fir, ranging from 25 to 75 years for the cooler, moister sites. Beaufait (1971) indicates fuels may accumulate at a rate of 3 to 5 tons per acre per year and will decompose at half that rate.

An extensive series of studies has investigated ways to extend the opportunities for burning larch-fir slash (Beaufait et al. 1975). In addition, study of understory burning was carried out by Norum (1974, 1975, and 1977), who inventoried the surface fuel loads. Total load of dead fuels ranged from 5.5 to 50 tons per acre. Fuels less than 3 inches in diameter made up 20 percent of the light loads and 16 percent of the heavy fuel loads. Under more severe burning conditions similar to wildfire situations, 96 percent of the total fuel was consumed.

Fuel inventory data taken in the Forest Service's Northern Region in 811 stands showed the following distribution of fuel by size class:

Size Class	0.25–1.0 inch	1.0–3.0 inches	3+ sound inches	3+ rotten inches	Total
			Tons/acre		
Average load	1.28	2.20	8.28	8.80	20.56
Maximum load	6.70	10.90	181.9	81.6	281.10

Lodgepole Pine

This species forms one of the most distinctive subclimax types of the Rocky Mountains. It occurs mainly at the middle elevations in the mountains in the Douglas-fir zone, but it also extends downward into the ponderosa pine type and runs well up into the spruce-fir type. The area it occupies has been increased greatly by fire; the type is most widely developed in the Rocky Mountain ranges. Dense stands have resulted after wildfire killed the stand but opened seed cones, releasing an abundant supply of seed (Lotan and Alexander 1973). Large quantities of fuels become available when either bark beetle or mistletoe attacks the stand at maturity or when trees reach a large diameter (Brown 1975). Muraro (1971) found that to predict surface fuel quantities stand histories from inception on were needed.

The frequency of fire in lodgepole pine stands appears to cover a wide span of time, but generally there is a longer period between fires than in ponderosa pine or Douglas-fir. Estimates are 500 to less than 100 years (Brown 1975), 25 to 200 years (Martin et al. 1976), and 50 to 150 years (Loope and Wood 1976). Fire potential does not necessarily increase with biomass but may peak one or more times before the stand becomes overmature and fire potential starts a steady increase. The maximum load of dead and down woody material recorded by Muraro (1971) for 10 stands was 26.5 tons per acre, with 35 percent less than 4 inches in diameter. In nine stands located in northern Idaho, Montana, and Wyoming, the maximum was 40.9 tons per acre with 23 percent less than 4 inches in diameter (Brown 1975). Summation of data taken during a dead and down fuel inventory in 765 stands showed the distribution of fuel by size class to be:

Size Class	0.25–1.0 inch	1.0–3.0 inches	3+ sound inches	3+ rotten inches	Total
			Tons/acre		
Average load	1.04	2.00	6.24	7.72	17.0
Maximum load	9.5	21.8	116.7	55.9	203.9

The nature of lodgepole pine stands suggests that fires generally consume large portions of the available fuel, kill the stand, reduce duff and litter to expose mineral soil, and trigger the release of seed so lodgepole assumes a fire climax position.

Englemann Spruce–Subalpine Fir

In the Rocky Mountains, this timber type ranges from the southern portion of the Yukon Territory to the high mountains of Arizona and New Mexico. South of Idaho and Montana, it is the uppermost timber type on sheltered sites. North of Utah and Wyoming, spruce occupies the lower moist sites and the subalpine fir extends above the commercial timber zone. Most forests of this type developed after fires, beetle epidemics, or other disturbances and may have two or more stories of trees. The spruce stands are some of the better timber producing sites in Montana while the subalpine stands have a greater variability in productivity, (Pfister et al. 1977).

In the high remote Selway-Bitterroot Wilderness fire tends to occur in this type at long intervals—100 to 250 years.[9] But at lower elevations fire frequency is similar to that in other areas such as those that include Douglas-fir. Fuel accumulation is slowed by the lower temperatures and short growing season, but mature stands can develop heavy loads—73 tons per acre. Over 90 percent of that load will be in duff and material over 4 inches in diameter (Habeck 1974). Fuel inventory work done in the Teton Wilderness during the summer of 1974 was tabulated by Oberheu[10] and showed the spruce-fir stands to average 66.4 tons per acre total fuel with about 7 percent being material less than 3 inches in diameter. These were high elevation stands (7,000 to 9,700 feet), and 56 percent of the fuel load was duff.

Forest Service's Northern Region fuel inventory data show fuel load by size class for 624 stands to be:

Size Class	0.25–1.0 inch	1.0–3.0 inches	3+ sound inches	3+ rotten inches	Total
			Tons/acre		
Average load	1.20	1.92	14.16	12.92	30.20
Maximum load	14.1	15.10	239.80	206.3	[1]475.30

[1] The maximum load summation is for all stands sampled and the maximum load in each size class did not necessarioly occur in the same stand.

[9] See footnote 6.

[10] Summary of Teton Wilderness by fuels, vegetation, topography, rate of spread, intensity, and burnout potential. Rough draft by Rick Oberheu, February 4, 1975. On file at the Northern Forest Fire Laboratory, Missoula, Mont.

Shrubland

The major shrubs of this area include the pinyon-juniper type, big sagebrush, shadscale (*Atriplex confertifolia*) and saltsage (*A. nuttallii*) with rabbitbrush (*Chrysothamnus* sp.), Gambel oak, ninebark (*Physocarpus* sp.), bitterbrush, and others (Kelly 1970) being more prominent in the Rocky Mountain region. The fuel load associated with various species has been receiving study and some estimates are possible (Brown 1976). Work discussed by Nord and Countryman (1971) illustrates the fuel potential of shrubs in the Intermountain area: manzanita (*Arctostaphylos* sp.), ceanothus, and other species may range from 5 to 12 feet tall with stems to 3 inches in diameter and fuel load between 15 to 30 tons per acre. Light brush stands like big sagebrush, fourwing saltbrush (*Atriplex canescens*), and similar species are usually less than 4 to 5 feet tall with stems less than 3 inches in diameter and fuel loads less than 15 tons per acre. Pinyon-juniper stands are not described in fuel loads but rather the number of trees per acre.

Just as trees exhibit the ability to withstand fire, shrubs tend to do the same. Basically, this is a function of whether the shrub is a seeder or sprouter, because the wildfire effect is to consume or kill back to the ground the shrub stems. Shrubs that reproduce by seed may produce an abundance of seeds after a fire; these are enhanced (Gratkowski 1961) if fires are not too frequent.

With frequent fire, many species that seed may be eliminated for long periods of time; for example, big sagebrush (Pickford 1932) and juniper (Johnson 1962). Species with durable seeds like ceanothus, pachistima, and ribes reseed quickly after fire (Roe et al. 1971). Other shrubs of this area may resprout after wildfire consumes or kills the aerial components. Among these shrubs are willows, (*Salix* sp.) bitterbrush, rabbitbrush, snowberry (*Symphoricarpos* sp.), and snowbrush ceanothus (*Ceanothus velutinus*) (Loope and Gruell 1973).

Fires generally consume all the dead shrub fuels under ½ inch in diameter (Brown 1972) and a decreasing fraction as diameter of shrub fuels increases. Nord and Countryman (1971) noted that fires do not usually consume live fuels greater than ½ inch in diameter. Variables critical to fuel consumption are: (1) Moisture contents of live and dead fuels, particularly the foliage and live twigs and dead fuels under ½ inch in diameter; (2) the quantity of live and dead fuel distributed within the shrub; and (3) the fuel load and distribution of litter

and grass under the stand. Fires occurring during drought and with high winds and/or on steep slopes consume more fuel and will develop greater intensities that affect the subsequent fuel quantities. Nord and Countryman (1971) state that the amount of fuel produced by brush stands is closely related to past fire history and to the type of vegetation that existed before burning. Wildfires generally occur under conditions when the fire effects will be most severe—low moisture contents, high temperatures, low humidities, and high fuel loadings. The shrub stand is burned or killed (to become dead and down woody fuel later), and set back to a grass community. Blaisdell (1953) showed sagebrush 12 years after burning to have only 10 percent of the coverage of unburned sites.

Shrub biomass by size class was investigated by Brown (1976) and 25 species of the northern Rocky Mountains were grouped into three classes. These were low, medium and high shrub—grouped according to heights observed in the field. Analysis of the data showed that shrub weight correlated better with stem basal diameter than stem length. Therefore, to estimate shrub weight, some measure of stem diameter is needed. Total above-ground weight and leaf weight can be estimated from equations of the form:

ln (weight, *g*) = *a* + *b* (*ln* (basal dia., cm)), and the fraction of total weight in the 0–0.5 cm and 0.5–2.0 cm branchwood classes can be determined by graphic methods. For each shrub class, the total weight estimate for maximum diameter sampled:

Low shrub, *ln* (weight, *g*) + 3.565 + 2.667 *ln* (basal diam. cm) max. diam. = 1.7 cm, weight/shrub = 145.6 gm

Medium shrub, *ln* (weight, *g*) = 3.580 + 2.853 *ln* (basal diam. cm), max. diam. = 3.8 cm, weight/shrub = 1617.7 gm

High shrub, *ln* (weight, *g*) = 3.507 + 2.679 *ln* (basal diam. cm), max. diam. = 6.3 cm, weight/shrub = 4774.1 gm

Big sagebrush and common juniper (*Juniperus communis*) were not included in the medium shrub group because their branch and leaf differ significantly from others in the group. Equations for these shrubs are:

Big sagebrush, *ln* (weight, *g*) = 3.161 + 2.242 *ln* (basal diam., cm), max. diam. = 6.9 cm, weight/shrub = 1792.7 gm

Common juniper, *ln* (weight, *g*) = 4.081 + 2.202 *ln* (basal diam., cm), max. diam. = 2.9 cm, weight/shrub = 617.4 gm

Similar data have been collected and reported by Storey (1969) for Utah juniper (*Juniperus osteosperma*) and pinyon. In addition, work has been conducted in cooperation between the Forest Service and Nevada Agriculture Experiment Station on controlled fire as a management tool in the pinyon-juniper woodland in Nevada.

The data now available are too few to allow estimation of shrub biomass by habitat type. Stand history and succession rate of change must be related to shrub biomass to reduce variability.

Grasslands

The problems presented by fire in forests and in grasslands are basically different. Forest fire problems center around the economic loss while grassland fires produce mainly a temporary loss of pasturage, which might even show gain after fire (Daubenmire 1968). Wildfires in grasslands often originate from lightning strikes (Komarek 1964, 1968) and their effect on fuels and vegetation is associated with the season, climate, quantity of dead vegetation, moisture content of the soil besides live and dead material, and the immediate weather, mainly relative humidity and wind. The frequency of fire has a significant effect on fuels in grasslands by shifting from perennials to annuals and affecting productivity so that recovery takes longer.

Vogl (1974) cites work by Coupland (1958), Lapham (1965), and Malin (1967), which show that grassland climates facilitate fires by the occurrence of dormant periods, dry seasons, and periodic droughts. From the data assembled and the literature reviewed, Vogl (page 153 in Kozlowski and Ahlgren 1974) describes the fire effects in grassland fuels:

> Despite the extensive fronts, roaring speeds, and ominous nature that grassland fires can assume, extremely high temperature at the plant and ground levels, complete consumption of all fuels, and damage to basal portions of plants and root stocks are uncommon . . . grassland fires generally produce a narrow belt of flames and pass rapidly . . . fires seldom tarry long enough to build high surface temperatures.

The quantity of fuels generated by fire effects and subsequent weather is influenced by the reactions of various grassland species to fire. Daubenmire (1968) observed that Palouse grasslands react differently than short-grass prairies; bunchgrass reactions contrast with those of sod grasses (Van Rensburg 1971); and cool-season grasses respond differently than warm-season grasses. Vogl (1974) reemphasizes that the time of burning and the frequencies of fire can be so critical that fire in some grasslands can be either beneficial or detrimental.

From field work on grasses, forbs, and small woody plants, Brown and Marsden (1976) showed the variability of grass load prediction by an R^2 (coefficient of correlation) of 0.30 and a coefficient of variation of 67 percent. The equation takes the form:

$$Y = 6.102 + 2.83X_1 + 2.432X_2$$
$$= G?m^2$$
$$X_1 = \text{ground cover, percent}$$
$$X_2 = \text{height, cm}$$

for grasses such as pinegrass (*Calamagrostis* sp.), elk sedge (*Carex geyeri*), and beargrass (*Xerophyllum tenax*). For 100 percent cover and a height of 30 centimeters, the load would be estimated at 362.1 grams per square meter (1.6 tons/acre). Work on the Beaverhead National Forest in southwestern Montana involving grasses and forbs (Payne 1974) resulted in regression equations for individual species and for the two groups, grasses and forbs. For grasses in general, the equation is:

$$\hat{Y} = 0.78 + 2.60X$$
$$= \text{grams per plot, gms per 20 dm}^2 \text{ plot}$$
$$X = \text{cover per plot, dm}^2 \text{ per plot}$$

With 100 percent cover or 20 square decimeter coverage per plot, the load would be 264 grams per square meter (1.3 tons/acre).

For a diverse group of areas with situations similar to those found in the Intermountain area, the conditions most commonly prescribed for burning are an air temperature of between 50° and 80°F, with a mean near 70°F, and a relative humidity usually between 20 and 60 percent, with a mean near 35 percent. The fine fuel moisture content range commonly was 5 to 15 percent, with the preferred level into the upper half of the range. For the air temperature and relative humidity cited above, the equilibrium moisture content of ponderosa pine needle litter on a drying cycle is about 9 percent and on a wetting cycle, 7 percent (Anderson et al. 1978). This is in agreement with the preferred fine fuel or ½-inch stick moisture content noted above. Citations of the above were found in Biswell (1963) for California understory burning in ponderosa pine; Biswell et al. (1973) for central Arizona understory burning in ponderosa pine; Ferry[12] for western Montana ponderosa pine understory of litter and pinegrass; Henderson (1967) for western Montana thinning of ponderosa pine; Kiil (1971) for slash burning of subalpine spruce fir in Alberta; Gartner and Thompson (1972) for Black Hills burning of grasslands and pine understory; Davis et al. (1968) for understory burning of ponderosa pine in Arizona; Leege (1968) for shrub burning for elk in north central Idaho; Gordon (1974) for moose habitat in Montana; Norum (1977) for understory burning in western larch-Douglas-fir; and Wright (1972b) for shrub burning in Texas. In addition, the guidelines suggested by Cooper (1963, 1975) and cited by Green (1970) for work by Schimke fall in the same range for the Southern United States from coast to coast.

Another fuel property that has become recognized as a critical variable on the fire effects is the moisture content of the lower duff layer. Only where fire has been used before (Biswell et al. 1973) or where an extreme fire condition is desired (Sellers and Despain 1974) has it been desirable for the lower duff and mineral soil to be dry.

In most cases, some moisture content level is specified or implied by the season or recent weather. Prescribed burning in the spruce forests of Finland (Sirén 1973) and the work by Norum (1977) in Montana show that lower duff moisture contents (40 percent or less) will leave only 2 to 3 centimeters of duff after a fire or will reduce duff depth by 50 to 100 percent depending on the amount of material less than 3 inches in diameter that is consumed (figs. 1 and 2 and table 12).

Within the range of safe and practical moisture contents found in field work, Norum (1977) states that about 78 percent of the material less than 3 inches in diameter is consumed in the fire. This finding was based on research results from 24 prescribed fires under standing timber (Norum 1974,

[12] Ferry, Gardner. 1969. Unpublished report on "BIA" Camas Prairie burn near Perma, Mont., on dry pine grass site. On file at the Intermountain Forest and Range Experiment Station, Missoula Fire Laboratory.

Table 12.—*Percentage of duff depth reduction (Norum 1977)*

Moisture content, lower half of duff	0- to 3-inch fuel loss (tons/acre)				
	0	5	10	15	20
		Percent			
5	0	61	79	90	100
10	0	59	78	90	100
15	0	58	78	90	100
20	0	56	78	90	100
25	0	53	77	90	100
30	0	51	76	90	100
35	0	49	75	90	100
40	0	46	73	90	100
45	0	44	71	89	100
50	0	42	68	88	100
55	0	39	65	87	100
60	0	37	62	85	100
65	0	35	58	83	99
70	0	32	54	81	99
75	0	30	50	78	99
80	0	28	45	74	98
85	0	26	41	69	97
90	0	25	37	65	96
95	0	23	33	59	94
100	0	21	29	53	92
105	0	20	26	48	89
110	0	18	23	42	86
115	0	17	20	36	83
120	0	16	18	31	78
125	0	15	16	27	74
130	0	14	14	24	68
135	0	13	13	21	62
140	0	12	12	19	56
145	0	11	12	18	50
150	0	10	11	17	44
155	0	10	11	16	39
160	0	9	11	16	34
165	0	9	11	16	30
170	0	8	11	16	27
175	0	8	11	16	25
180	0	7	11	16	23
185	0	7	11	16	22
190	0	7	11	16	22
195	0	6	11	16	21
200	0	6	11	16	21
205	0	6	11	16	21
210	0	6	11	16	21
215	0	5	11	16	21
220	0	5	11	16	21

1975) and 61 broadcast-burned clearcuts (Beaufait et al. 1977). The less than 3-inch fuel load range was 1 to 8 tons per acre and the less than 4-inch fuel load was 5 to 21 tons per acre, respectively. On the clearcut units, the greater-than-4-inch fuels made up 88 percent of the total load that, exclusive of duff, ranged from 60 to 165 tons per acre. Sampling limitations prevented accurate evaluation of total fuel reduction. For burning under standing timber, Norum (1974) developed a regression equation to estimate the total fuel loss:

$$\hat{Y} = 2.5 + 31.7X_1 + 1.1X_4 - 0.019X_{13} = Kg/m^2$$

where X_1 = 0− 1/4 inch (.635 cm) preburn weight, Kg/m^2

X_4 = 3-inch and greater rotten weight, Kg/m^2

X_{13} = moisture content of lower duff

If fuel inventory provides the total preburn fuel weight and the quantity in the size classes along with the moisture content of the lower half of the duff layer, then an estimate of fuel reduction is possible. For use of fire, the guidelines presented by Norum (1977) appear to be most useful in larch–Douglas-fir stands.

General agreement with the observation of a 78 percent reduction of material less than 3 inches is found in other works. Cooper (1975) indicates about a 67-percent reduction of understory fuels using a backing fire; Gordon (1974) found a 90- to 100-percent consumption of fine fuels and 25- to 50-percent consumption of heavy fuels by observation; Gartner and Thompson (1972) found a 70-percent reduction in the preburn load of 5 to 6 tons per acre of material

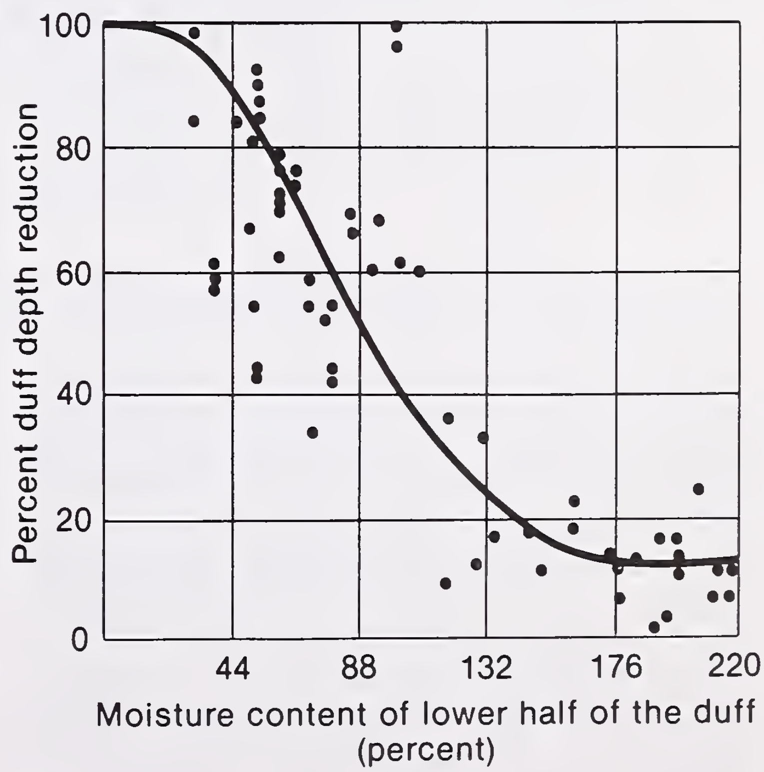

Figure 1.—Percentage of preburn duff depth reduced by broadcast fires versus the moisture content of the lower half of the duff. Curve fitted to experimental data (Norum 1977).

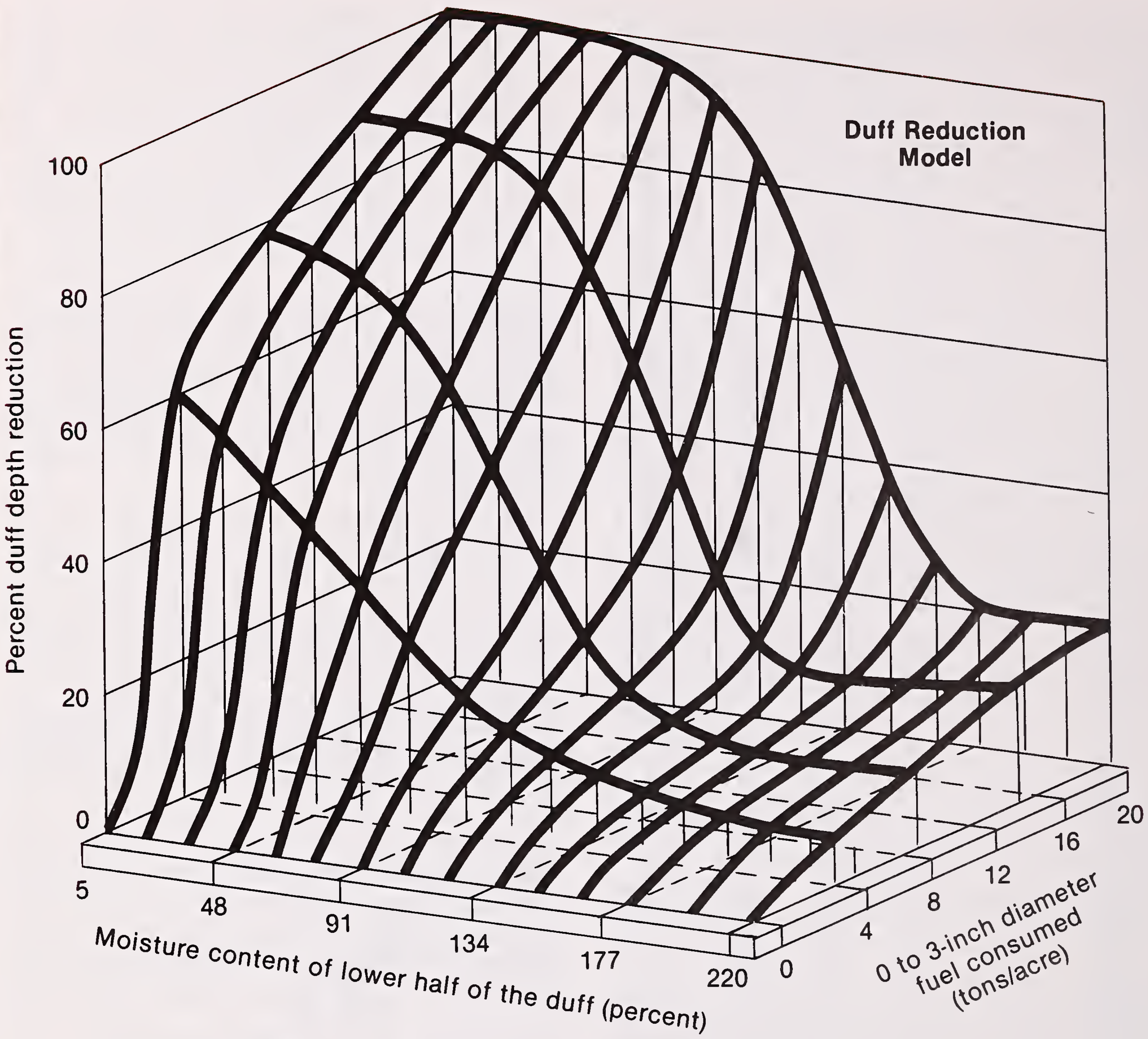

Figure 2.—Percentage of duff reduction as it varies with combinations of moisture content of the lower half of the duff and the amount of 0- to 3-inch diameter down, dead, and woody fuels consumed (Norum 1977).

less than 2 inches; Biswell (1963) cites a 76-percent reduction in needle litter and 23-percent reduction in the duff under ponderosa pine stands; Kiil (1975) measured fuel weights and consumption in a black spruce stand and indicates an 82-percent reduction in fuel, exclusive of duff, with an original load of about 8 tons per acre.

If the moisture content of the lower duff layer can be measured and the fraction of 3-inch material consumed can be estimated, then the fraction of duff removed can be predicted (Norum 1977). This can be done by adopting the work of Albini (1976) who presented a burnout model that predicts the fraction of gross load remaining. Works by Stocks and Walker (1972), Van Wagner (1972), and Countryman (1969) were used to develop the model and provide some experimental checks. The burns reported by Norum (1975) provided additional checks and are discussed fully in Albini's publication. It appears fuel consumption and burnout can be estimated if sufficient fuel data or correlations are available to input fire models such as those developed by Rothermel (1972) and modified by Albini (1976).

Fire effects that are desired cannot be achieved unless certain conditions are met. Among these is the minimum amount of fine fuel necessary for fire to spread. Again for a variety of locations, pre-

scribed burners have observed that fine fuels uniformly distributed must be greater than 600 pounds per acre to get the desired fire effect. In Nevada, burning sagebrush needed 600 to 700 pounds of fuel in early spring burns (Beardall and Sylvester 1976); Gordon (1974), in burning for moose habitat, slashed timber to provide continuous fine fuels; Wright et al. (1972) noted at least 1,000 pounds per acre needed to carry fire; Cooper (1963) noted in the south 2,000 pounds per acre fine fuels were needed to meet goals; Leege (1968) observed that a good layer of fines is needed to burn brush for elk habitat. Several times it was noted that as fine fuel load decreases, winds need to be higher for fire to spread.

Severe Fire Effects

Fire can effectively reduce fuels and other vegetation when conditions are maintained within the limits such as noted above. As we start to move toward more severe burning conditions, more of the preburn fuel will be consumed but the post-fire fuels may be sharply increased. Overstory materials start to be involved and quantities of standing dead snags and stems result. While 70 percent of the duff was removed by fire in Arizona (Davis et al. 1968), 80 tons per acre of dead trees were produced. Crowning and scorch do provide a fire effect that creates fuels and the prediction of the potential is being developed. The work of Van Wagner (1973) has been used by Albini (1976) and Norum (1977) to estimate crown scorch heights and has been useful in field applications. Torching-out and crowning are under study by Albini, Van Wagner, and others. An initial torching-out model and spot-fire prediction method was used at the 1978 Fire Behavior Officer School.[13] The potential for scorch height is related to flame length, which can be predicted from Byram's fireline intensity (Byram 1959):

$$L = 0.45\,(I)^{0.46}, \text{ ft.}$$
$$\text{where } I = \text{Btu/ft/sec.}$$

Knowing fireline intensity and the air temperature, then Van Wagner's (1973) formula can be used:

$$H_s = (63/(140\text{-}T)(I^{7/6}/(I + W^3)^{1/2}), \text{ ft.}$$

where T = ambient air temperature, ° F
W = windspeed at 20 ft.
H_s = maximum height of lethal scorch, ft.

[13] Anderson, H. E. 1978. Lesson plan for 1978 Fire Behavior Officer School, Marana, Ariz.

It has been noted several times in the literature that mortality increases when more than two-thirds of the crown length is scorched. Sirén (1973) shows the percent needle damage as functions of tree height, slash and understory, amounts of fuel, and time of day. He found, as have others, that cambium damage also can create new fuels by killing small trees and injuring the more mature stand so insects may invade (Norum 1974, 1975).

The analysis of data collected by Norum (1975) was used to predict the fire injury and survival of interior Douglas-fir and a manuscript is in process by Collin Bevins. The probability of survival is calculated by:

$$P = (1 + \mathrm{EXP}(0.1688 - 5.002X_1 + 0.0932X_2))^{-1}$$

where P = probability of survival (1 = survival, 0 = dead),
X_1 = bark thickness at d.b.h., can be estimated by 0.06345 × d.b.h. (inches).
X_2 = crown scorch height (feet)

or by $P = 0.32 - 0.520X_1 = 0.672X_2$
X_1 = fraction of live crown scorched
X_2 = bark thickness (inches)

Fire effects on fuels cause reduction in the fraction of preburn quantities by size class and strata. The interaction of fire with dead fuels results in consumption or death of live vegetation and can create a severe fire problem due to new fuel regeneration. Tools are becoming available so that fire effects on fuels can be reliably assessed.

Research Needs

One area of much concern and posing a challenge to research is the assessment and prediction of firebrand generation and spot-fire production. Investigations of firebrand flight and burning characteristics have pretty well defined what brands of various sizes can do (Muraszew et al. 1976, Tarifa 1967, Lee and Hellman 1970). However, what will be generated in the natural fuel situations and the quantity of brands is largely unknown. Ignition potential of firebrands on receptors such as grass, rotten wood, and needle litter has been investigated (Stockstad 1975, 1976). What percent coverage exists in the field is unknown. Data are being collected, and activities at the Northern Forest Fire Laboratory include this as a problem area.

Pacific Coast States

The Pacific Coast States include Alaska, Hawaii, Washington, Oregon, and California. A wide range of vegetative types is represented. Few data on the effects of fire on fuels are available for Alaska and Hawaii.

Fuel Types and Fire Activity

Discussions of vegetation types in the contiguous Pacific Coast States range from the sparse vegetation of the deserts through shrub-grass and chaparral and open pine types to wet coastal forests.

The USDA Forest Service (1973) indicates the followi.g acreages of commercial timber in the contiguous Pacific Coast States.

Species	*SAF cover type*	*Thousand acres*
Fir–spruce	206, 208, 211	8.0
Larch	212	0.7
Western white pine	215	0.2
Lodgepole pine	218	3.3
Western hemlock–Sitka spruce (*Picea sitchensis*)	225	9.9
Douglas-fir	229	18.9
Redwood (*Sequoia sempervirens*)	232	0.8
Ponderosa pine	237	13.5
Western hardwoods		8.5
Nonstocked		3.7
Total		67.5

The types given by the Forest Service do not agree completely with SAF Cover Types, but the figures give an idea of the acreages involved. In addition to these acreages, there are probably 40 million acres of rangeland in these States, where fire and fuels are important.

The historical and ecological role of fires in the different vegetative types varies greatly. The coldest or wettest areas generally experience infrequent, high-intensity fires which kill most trees and set vegetation back to the pioneer stages of secondary succession. Periods between fires may be from 25 years to several hundred years (Martin et al. 1976). As conditions change to warmer or drier situations, fire frequency increases. Average periods between fires range from 30 to 45 years in higher, wetter ponderosa pine types (Weaver 1959, 1961; Soeriaatmadja 1966) to 5 to 15 years in lower, drier pine types (Weaver 1959, 1961; Soeriaatmadja 1966; Hall 1976; Martin and Johnson 1979). As the forest yields to sagebrush-grass types, fire frequency appears to be the same as in the lower, drier pine types (Martin and Johnson 1979). Where sites become very dry, however, the period between fires tends to increase because not enough fuel is produced to carry fires.

Alaska

Viereck et al.[14] evaluated the effects of the 1971 Wickersham Dome fire on vegetative fuels in the black spruce (SAF Cover Type 204) and aspen (SAF Cover Type 203) of the taiga. They trace the biomass of several plant species following fire and in a control area without fire. Fuel loads of trees and changes in them are not given, but these could be calculated from data on tree size and spacing. When the manuscript is published, it will contain very useful data on fuel consumption and progressive development of fuels following fire.

Barney and Van Cleve (1973) collected data on fuel weights and biomass of black spruce stands in interior Alaska. These data could be combined with those from the Viereck report in estimating total fuel consumption by the Wickersham Dome fire.

Hawaii

The effects of fire on vegetation can be of some help in approximating the effects of fire on fuels. Wood et al. (1969) evaluated revegetation of a burn following a wildfire in June of 1967 on Kauai. Six months after the fire, 94 percent of the burned area had 50 percent or more living plant cover. Fireweed (*Erechtites hieracifolia*) was the dominant plant for the first year or two and koa (*Acacia koa*) seedlings became established. Uluhe fern (*Dicranopteris linearis*), which develops very hazardous fuel complexes, apparently was almost completely killed by the fire. Scowcroft and Wood (1976) discuss reestablishment of koa after two burns in Oahu.

Fujioka (1976) discusses dead fuel moisture con-

[14] Viereck, Leslie A., and 15 others. Effects of fire on interior Alaska forest communities. A summary of the results of the Wickersham Dome Fire Studies. Manuscript, 160 p., typewritten.

tent of broomsedge (*Andropogon virginicus*) and its relationship to atmospheric conditions. The moisture content of fine fuels such as broomsedge would influence both fire behavior and fuel consumption.

Fir-Spruce

Kilgore (1971) discussed the role of fire in managing red fir forests. Twelve 100 by 100 foot plots were burned to evaluate effects of fire on vegetation and fuels. Numbers of fir saplings were reduced by more than 60 percent by burning, from 12,000 to 4,900 per acre. Flash fuels and duff were reduced by more than 50 percent from a pre-fire level of about 30 tons per acre. The volume of downed logs was reduced 30 to 50 percent.

Giant Sequoia

Kilgore and Sando (1975) report a significant reduction in fuels and subsequent potential for high intensity surface and crown fires following prescribed burning in three sequoia (*Sequoia gigantea*) plots. Surface fuels were reduced from 90.8 to 13.4 tons per acre, while live crown fuels below 55 feet height were reduced from 8.0 to 3.5 tons per acre. Greatest fuel reductions were in the duff (reduced from 42.1 to 5.2 tons per acre) and fuel size classes greater than 2.5 inches (reduced from 43.5 to 6.7 tons per acre).

Parsons (1978) reported fuel accumulation in giant sequoia (*Sequoia gigantea*) stands following fire (tables 13 and 14).

Table 13.—*Accumulation of downed woody material per acre (from Parsons 1978)*

Time since fire	Size Class (inches)			
	0–0.25	0.25–1	1–3	3+
	Tons			
Unburned[1]	0.257	1.872	3.040	50.72
Immediate postburn	.101	.258	.476	6.11
1 year	.116	.380	.635	6.46
4 years	.503	1.373	1.177	9.19
7 years	.404	1.764	2.323	27.38

[1] Unburned for more than 60 years; exact date of last burn unknown.

Burning had reduced all surface fuels (dead and down and litter and duff) from 85 to 9.3 tons per acre. In 7 years, total surface fuels had returned to 45 tons per acre. The sites had not been burned for 60 years previous to the prescribed burns, however, so much of the buildup of fuels following the prescribed burns may have been from understory killed by the fire.

Table 14.—*Litter and duff accumulation following different periods since burning (from Parsons 1978)*

Time since fire	Depth	Weight per acre
	Inches	*Tons*
Unburned[1]	1.9 ± 0.31	29.1 ± 3.6
Immediate postburn	.2 ± 0.1	2.4 ± 0.6
1 year	.3 ± 0.1	4.2 ± 1.6
4 years	.7 ± 0.1	10.3 ± 1.4
7 years	.9 ± 0.1	13.1 ± 2.0

[1] Unburned for more than 60 years; exact date of last burn unknown.

Southern California Chaparral

The term chaparral may represent many different shrub species growing as pure or mixed types. Generally, chaparral represents types which are very flammable and dangerous under certain weather conditions. Reduction of fuel loads in chaparral, particularly by burning, may be the most rational means of reducing large, disastrous fires. Chaparral fuel modification by fire has been the subject of studies in southern California.

Chandler (1957) reported on three fires conducted at Camp Pendleton along the southern California coast (table 15). The sage sites burned almost completely at 38 percent relative humidity, whereas essentially no fuel was consumed in the California scrub oak (*Quercus dumosa*) sites burned at 65 percent relative humidity. Results were intermediate in the chamise (*Adenostoma fasciculatum*).

Buttery et al. (1959) reported on kill of chamise plants following crushing, burning in different seasons, and chemical spraying. Although their results do not indicate the direct effect of fire on fuels, the long-term effect on buildup of fuels is indicated from their data on sprouting and plant kill.

Further work on fuel reduction by fire in chaparral was reported by Green (1970). The area burned was dominated by 5- to 6-foot tall chamise with scattered 6- to 7-foot tall bigberry and Eastwood manzanita (*Arctostaphylos glauca* and *A. glandulosa*). Scattered patches of mountain-mahogany (*Cercocarpus betuloides*) and scrub oak were present, as well as other occasional shrubs. The test plot was burned in late May at 2 p.m. with temperature of 80° F, relative humidity of 28 percent, and wind of 10 to 12 miles per hour. Fuel stick moisture content was 10 percent. Fuel consumed ranged from 40 to 85 percent of the live fuel and 95 to 100 percent of the dead fuel (table 16).

The equations of Rothermel and Philpot (1973), predicting the changes in fuel load and flammability

Table 15.—*Dry weight of fuel before and after burning in three types of vegetation, Camp Pendleton, San Diego County, Calif., 1954 (from Chandler 1957)*

Type	Date	Relative humidity	Wind velocity	Fuel before burning	Fuel after burning	Fuel remaining
		Percent	*Mi/h*	*Tons/acre*	*Tons/acre*	*Percent*
Scrub oak	8/12	65	8	40.4	40.4	100
Scrub oak	8/12	65	8	46.8	46.8	100
Sage	9/15	38	5	12.6	0.7	6
Sage	9/15	38	5	13.8	1.3	9
Chamise	9/30	33	7	20.5	3.8	19
Chamise	9/30	33	7	13.0	6.4	49

Table 16.—*Average fuel volumes of principal brush species before and after prescribed burning, North Mountain Experimental Area, Calif. (from Green 1970)*

Species	Standing live brush				Dead brush		Total fuel		Fuel consumed	
	Pre-burn	Post-burn	Pre-burn	Post-burn	Pre-burn	Post-burn	Pre-burn	Post-burn	Live brush	Dead brush
	Feet (average height)		*Tons/acre*		*Tons/acre*		*Tons/acre*		*Percent*	
Chamise[1]	6.0	2.0	15.0	2.0	4.0	0.2	19.0	2.2	85	95
Manzanita	6.5	3.5	4.0	1.0	1.0	0	5.0	1.0	75	100
Mountain-mahogany	11.0	9.0	3.5	2.0	2.0	.1	5.5	2.1	45	95
Scrub oak	12.0	11.0	5.0	3.0	.5	0	5.5	3.0	40	100
Total			27.5	8.0	7.5	0.3	35.0	8.3	70	95

[1] Includes desert ceanothus (*Ceanothus greggii*) and traces of other species estimated to occupy about 3 percent of the area.

over time, are one of the best examples we have of a dynamic fuel model. From their equations, one could predict the fuel load and flammability of southern California chaparral for 50 years following fire. Their equations for fuel are:

Loading Over Time

Chamise Stands

$w_n = 0.0459A/(1.4459 + 0.0315A)$

Mixed Stands

$w_n = 0.0459A/(0.4849 + 0.0170A)$

Fraction Dead

Average Mortality

$F_d = 0.0694\ exp\ (0.0402\ A)$

Severe Mortality

$F_d = 0.1094\ exp\ (0.0385\ A)$

Fraction Total By Size Class

Dead Fuel

$F_{d.0\text{–}1/4} = 0.347 F_d$

$F_{d,\ 1/4\text{–}1/2} = 0.364\ F_d$

$F_{d,\ 1/2\text{–}1} = 0.207\ F_d$

$F_{d,\ 1\text{–}3} = 0.085\ F_d$

Living Fuel

$F_{l,\ \text{leaves}} = 0.1957 - 0.305\ F_d$

$F_{l,\ 0\text{–}1/4} = 0.2416 - 0.256\ F_d$

$F_{l,\ 1/4\text{–}1/2} = 0.1918 - 0.256\ F_d$

$F_{l,\ 1/2\text{–}1} = 0.2648 - 0.050\ F_d$

$F_{l,\ 1\text{–}3} = 0.1036 - 0.114\ F_d$

Seasonal Changes Living Fuel

$M_{l,\ \text{leaves}} = 1/(0.726 + 0.00877\ D)$

$H_{l,\ \text{leaves}\ cf}1/4 = 9613 - 1.00\ D + 0.1369\ D^2 - 0.000365\ D^3$

$M_{l,\ \text{stems}} = 1/(1.454 + 0.0065\ D)$

$H_{l,\ 1/2\text{–}3} = 9509 - 10.74\ D + 0.1359\ D^2 - 0.000405\ D^3$

Definition of Symbols

w_n = net loading (lb/ft^2)

A = age of stand in years

F_d = dead fraction of net load

F_l = living fraction of net load

D = number of days since May 1

M = moisture content, fraction dry weight

H_l = heat content, Btu/lb

The equations would essentially show that live fuel builds up rapidly at first and later at a less rapid rate. Dead fuel, on the other hand, accumulates slowly at first but then at an ever increasing rate.

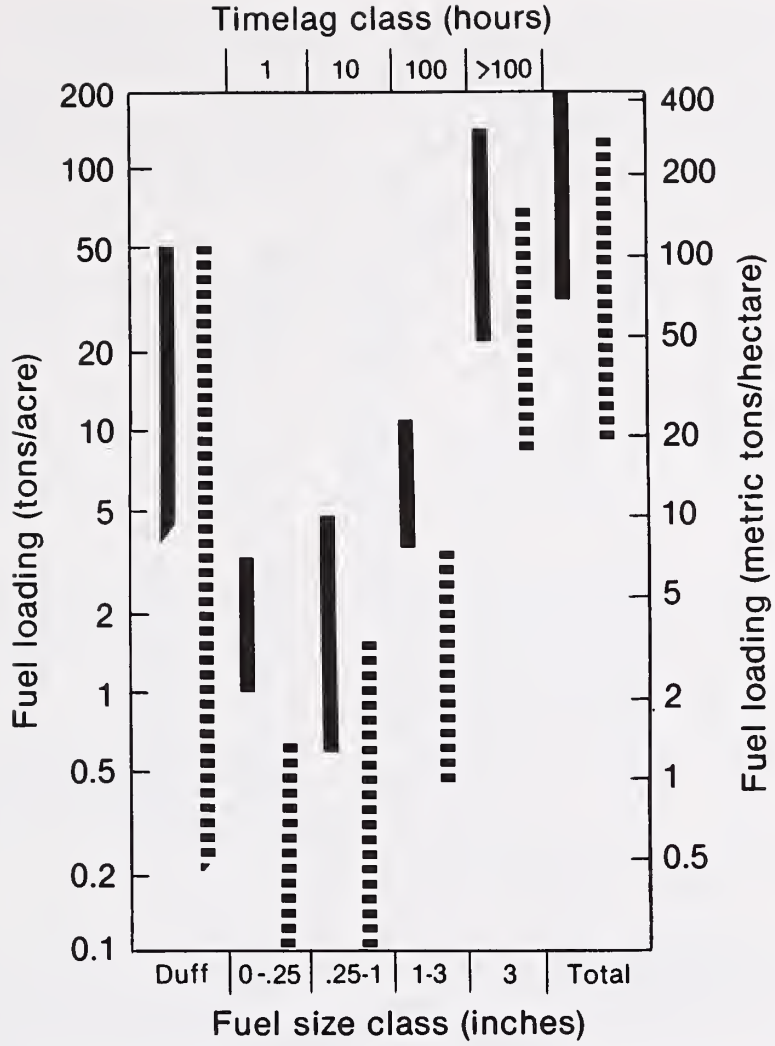

Figure 3.—Amount nd consumption of various residue components by broadcast burning. Note that the vertical scale is logarithmic, which reduces the visual effect of the fuel comsumption. Solid bars represent range of fuel amounts before burning; striped bars represent the amount after. Data condensed from Beaufait et al. (1975) and Bevins (1976) (from Martin 1977).

For example, at 15 years of age, only about 15 percent of the total fuel in chamise would be dead. However, by age 30 over 20 percent would be dead fuel and by age 50 over 50 percent of the total fuel load would be dead material.

Western Slash

Martin (1977) summarized fuel consumption in slash burning in studies by Beaufait et al. (1975) and Bevins (1976) (fig. 3). These burns were conducted mostly in western Montana by Beaufait in larch–Douglas-fir clearcuts (SAF Cover Type 212). The data in Bevins' report summarized all information he could collect, mostly from western Oregon and Washington in Pacific Douglas-fir (SAF Cover Type 229), Douglas-fir–western hemlock (SAF Cover Type 230), western redcedar–western hemlock (SAF Cover Type 227), and western redcedar (SAF Cover Type 228).

Duff fuel loads before burning ranged from less than 4.5 to 50 tons per acre and consumption ranged from 0 to 95 percent. Martin rounded consumption of the different fuel size classes to the nearest 10 percent with the following results:

Fuel size class	Preburn fuel load range	Postburn fuel load range	Rounded average consumption
	Tons/acre	*Tons/acre*	*Percent*
Duff	< 45–50	< 0.2–50	0–95
1 hr. time lag (T.L.)	1–3	< 0.1–0.6	90
10 hr. T.L.	0.6–4.5	< 0.1–1.6	80
100 hr. T.L.	3–11	0.4–2.9	70
> 100 hr. T.L.	21–134	7.6–67	60

Table 17.—*The total fuel complex in the Pasayten Wilderness (Fahnestock 1976)*

		Fuel loading						Fuel rating[1]			
		Dead fuels				Live crown[3]	Total	Keys[4]		R–6[5]	
Unit	Age	Fine	Coarse	Duff[2]	All			R/S	C/P	R/S	R/C
	Years			*Tons/acre*							
Abies-Vaccinium habitat type:											
9	30	2.9	24.2	21.5	48.6	0	48.5	1.0	2.0	1.0	1.0
6	66	2.0	31.8	24.0	57.8	1.7	59.5	1.0	0	1.0	1.0
1	175	9.1	10.8	26.2	46.1	8.9	55.1	5.7	2.0	1.0	1.0
10	200	.7	20.3	19.1	40.1	12.4	62.5	1.8	4.0	1.0	1.0
Abies-Pachistima habitat type:											
8	2	2.8	13.9	10.4	27.1	0	27.1	1.0	5.0	1.0	1.0
11	27	3.8	98.6	13.2	115.6	1.5	117.1	11.5	[6]0	4.4	3.4
16	44	2.1	5.2	15.6	22.9	3.2	26.1	2.6	4.2	3.8	1.7
17	44	2.9	37.0	16.5	56.4	4.6	51.0	6.8	5.7	2.8	2.1
18	44	4.8	69.3	5.8	79.9	3.5	83.4	4.6	5.7	3.8	3.6
14	55	3.0	99.2	39.6	141.8	6.1	147.9	4.7	4.0	5.0	4.0
2	57	1.2	98.4	33.5	133.1	5.1	138.2	1.8	6.6	1.0	2.3
5	120	5.6	40.6	48.1	94.3	17.6	111.9	6.6	6.6	9.6	1.2
3	190	.5	58.3	49.7	108.5	16.3	124.8	3.0	2.6	1.0	2.1
7	200+	1.6	67.1	49.9	115.6	11.3	126.9	1.0	4.0	1.0	4.0
15	245	3.4	58.1	34.6	96.1	10.3	106.4	3.4	4.0	2.2	3.8
12	277	4.0	72.0	35.4	111.4	10.5	121.9	12.1	2.7	3.4	3.4
4	300	2.3	69.0	50.1	121.4	12.7	134.1	1.0	4.2	1.0	3.7
13	400	3.5	116.0	44.3	153.8	15.8	169.6	2.9	5.0	1.0	2.9

[1] R/S = rate of spread, C/P = crowning potential, R/C = resistance to control.
[2] Duff = forest floor. Estimated on basis of 1 cm depth = 13,000 kg ha^{-1} (Wooldridge 1970).
[3] Material ≤ 2 inches in diameter.
[4] On relative scale of 100 for R/S, 10 for C/P (Fahnestock 1970).
[5] Descriptive terms and numerical equivalents are (USDA Forest Service 1968):

	Low	Medium	High	Extreme
R/S	1	5	25	125
R/C	1	2	4	8

[6] Trees less than 20 feet tall; flammability of crowns rated by R/S.

These burns represent a wide range of fuel types, fuel loads, and burning conditions, and consumption of any component could vary greatly. For example, Beaufait recorded 44 to 98 percent consumption in the 0 to 10 centimeter (0 to 4 inch) size class fuels for 65 plots, with an average of 81 percent consumption.

Engelmann spruce-Subalpine fir

Fahnestock (1976) recorded surface fuels in the Pasayten Wilderness Area of northcentral Washington. The entire area falls in the subalpine fir zone (Franklin and Dyrness 1973), but sites may be dominated by Douglas-fir, Engelmann spruce, or lodgepole pine as well as subalpine fir. Fine dead fuel load above the forest floor ranged from 0.5 to 9.1 tons per acre (table 17). The duff or forest floor ranged from 5.8 to 50.1 tons per acre and 0.71 to 3.41 inches in depth. Coarse dead and down fuels ranged from 5.2 to 106.0 tons per acre. Fine fuels showed no correlation with stand age (or time since fire). The duff built up for about 100 years and then remained relatively constant. Coarse fuels, on the other hand peaked between 25 and 60 years, then dropped sharply until about 125 years, after which they again rose gradually to the early peak by about 350 to 400 years. The early peak was probably caused by falling of the stand killed by fire; the later peak by decadence of the stand.

Mixed conifers

Fuels represented in this zone often are not mixed conifer species, but actually ecologically seral species. Fahnestock (1976, 1977) recorded down and dead fuels in stands of various ages after wildfires that killed the stands. The stands ranged in ages from 2 to 400 years and down and dead fuels ranged from 0.7 to 9.1 tons per acre of fine fuels and 5.2 to 108 tons per acre of coarse fuels. Coarse and total fuel loads peaked 40 to 50 years after fire as dead trees fell, and then rose again after 200 to 300 years as the fire-established stand became decadent. Fine

fuel loads were quite low throughout. The forest floor load increased rapidly after 40 or 50 years to a level of 35 to 50 tons per acre.

Prescribed burning was used by van Wagtendonk (1972) to evaluate the effects on 4 ecosystems of Yosemite National Park. Burning conditions were set by fuel stick moistures with the following reductions in fresh needle layer:

Fuel stick moisture	Fuel Type							
	Bear Clover		Needle		Valley		Incense Cedar	
Percent	*Tons/acre*	*Percent*	*Tons/acre*	*Percent*	*Tons/acre*	*Percent*	*Tons/acre*	*Percent*
19	0.71	76.2	0.53	25.7	0.44	31.0	0.22	18.8
16	1.05	88.0	1.69	83.4	0.45	25.6	0.25	22.1
13	1.53	100.0	2.24	98.9	1.34	68.2	0.40	42.6
10	2.10	92.2	1.72	98.6	1.47	83.7	1.97	97.4

He recorded effects on low vegetation, recording from 28 to 100 percent reduction of it, and went on to discuss the effects of fire on many aspects of the ecosystems.

Agee (1973) reported fuel reduction when burning in ponderosa pine-incense cedar and in white fir-giant sequoia types. Fuel weight reductions were recorded as aerial, litter, and duff for all fuels less than 0.39 inches diameter. Both open stands (less than 12 stems or 40.5 ft^2 basal area per acre) and dense stands were burned with fuel stick moistures at 10 and 13 percent with the following results:

Fuel component and fuel stick moisture	Ponderosa pine-incense cedar				White fir-giant sequoia			
	Open		Dense		Open		Dense	
	Fuels before	Reduction	Fuels before	Reduction	Fuels before	Reduction	Fuels before	Reduction
Percent	*Tons/acre*							
Aerial								
13	0.13	0.0	0.6	0.0	0.0	0.0	0.3	0.06
10	0.13	0.14	0.6	− 0.5	0.0	− 0.02	0.3	− 0.5
Litter								
13	11.2	0.8	7.6	0.3	16.0	13.7	12.9	0.8
10	11.2	4.1	7.6	5.7	16.0	3.3	12.9	− 1.4
Duff								
13	27.3	6.8	15.6	3.8	27.0	18.9	23.3	9.1
10	27.3	15.2	15.6	15.1	27.0	− 0.6	23.3	4.9

Kilgore (1973) discussed the ecological role of fire in Sierran conifer forests. He relates the average period between fires of about 8 years to the level of fuel accumulation such that wildfires of relatively low intensity would occur. He presents a table of seedling establishment, which would contribute to fuel buildup, following burning.

Agee and others (1978) indicate litterfall showed no apparent differences between 4 species of Sierra Nevada conifers (ponderosa pine, sugar pine, giant sequoia and white fir). Fuel loads before burning ranged from 7.0 to 10.7 tons per acre of litter and 6.7 to 14.2 tons per acre of duff. Fuel load before burning and percent reduction of fuels was as follows:

	Fuel load		Consumption	
	Litter	Duff	Litter	Duff
	Tons/acre		*Percent*	
Ponderosa pine	7.7	14.2	65–79	46–74
Sugar pine	7.5	12.4	44–80	72–96
White fir	10.7	12.6	69–81	60–97
Giant sequoia	7.0	6.7	60–87	−15–98

Ponderosa pine—larch—Douglas-fir

Williams and Martin[15] and Williams (1978) indicate 0- to 3-inch diameter fuels were reduced from 5.0 to 3.6 tonnes per hectare (2.2 to 1.6 tons per acre) on four plots in wet fall burns. Fuels greater than 3-inches diameter were reduced from 26.4 to 11.4 tonnes per hectare (11.8 to 5.1 tons/acre) and duff from 26.2 to 16.9 tonnes per hectare (11.7 to 7.5 tons/acre) on the same plots. Only small understory ponderosa pine and Douglas-fir trees were killed by the fires. Percent of the two species killed by size class are represented by the equations:

Douglas-fir $M = 72.13 - 31.13\, ln\, d$

Ponderosa pine $M = 53.57 - 24.36\, ln\, d$

where, M = mortality in percent
ln = natural logarithm
d = diameter in centimeters 4.5 centimeters (1.8 inches) above the ground

Fire and fuel conditions are documented in the report.

Lodgepole pine

Lawson (1973) reported on 28 test fires conducted on three sites in lodgepole pine in British Columbia. A wide range of burning conditions were used to evaluate the effects on fire behavior. Fuel consumption was not included in his regressions, so the burning conditions, fire behavior, and consumption are given for each plot (tables 18 and 19). He also indicates a great number of the overstory lodgepole pine and understory trees were killed. These, of course, will be contributing to surface fuel components in the future.

Woodard (1977) reported on the effects of a prescribed burn in a lodgepole pine snag area and adjacent thicket area which were burned to improve summer elk habitat. Both areas were in a *Picea engelmannii-Abies lasiocarpa-Carex geyeri* habitat type, but must fall in the SAF lodgepole pine type because of the dominance of lodgepole on the site. The snag and thicket areas, totaling about 10.9 hectares (27 acres), were burned under the following conditions:

Date:	September 30
Temperature:	61° to 63° F
Relative humidity:	19 to 21 percent
Wind:	Calm to 16 miles per hour
Days since rain:	15
1 hr. T.L. fuel moisture:	13.1 percent
Firing pattern:	Backfire and strip head fire

Fuel loads before burning and the percent reduction were:

Down and dead fuel class	Before burn Average	Standard deviation	Standard error of mean
	Tons/acre		
Snag area			
1 hr. T.L.	0.9	0.4	0.09
10 hr. T.L.	2.9	1.34	0.3
100 hr. T.L.	5.1	2.8	0.7
> 100 hr. T.L., rotten	30.9	26.7	6.5
> 100 hr. T.L. solid	49.8	64.7	15.7
Total of above	89.5	71.2	17.3
Duff	30.0	14.6	3.5
Thicket area			
1 hr T.L.	0.6	0.1	0.04
10 hr. T.L.	2.1	1.4	0.4
100 hr. T.L.	4.4	3.5	1.0
> 100 hr. T.L., rotten	17.4	18.4	5.1
> 100 hr. T.L., solid	17.0	21.1	5.8
Total of above	40.7	23.4	6.5
Duff	36.2	14.5	4.0

Fuel consumption in the snag area averaged 50.3 percent for all down and dead fuels, with a range of 12.7 to 97.3 percent consumption for the different plots. In the thicket area, 49.8 percent of the down and dead fuels was consumed with a range of 0 to 84.1 percent consumption on the different plots. A significant factor in future fuel loads will be the transition of trees killed by the fire from live aerial fuel to dead aerial fuel and finally to down and dead fuel over time. The progression of fuels should be similar to that found by Fahnestock (1977).

Western hemlock

Hedin and Turner (1977) measured slash consumed by a broadcast burn of old-growth western

[15] Williams, J. T., and R. E. Martin. 1978. Final report submitted to Douglas-fir Tussock Moth Program, Portland, Oreg.

Table 18.—*Fire behavior and fire environment data (from Lawson 1973)*

Plot[1] number	Mean heading R.O.S. uncorrected for growth	Mean heading R.O.S. corrected for growth	Mean head fire intensity	Heading flame length	Heading flame depth	Stand wind	Open[2] wind	Air temperature at 4 feet	R.H. at 4 feet	Surface litter M.C.	Upper organic layer M.C.	Danger Indices: Fine fuel moisture code	Danger Indices: Duff moisture code	Danger Indices: Initial spread index	Danger Indices: Fire weather index
	Ft/min	*Ft/min*	*Btu/sec/ft*	*Feet*	*Feet*	*Mi/h*	*Mi/h*	°F	*Percent*	*Percent*	*Percent*				
109	0.9	1.3	14	1.4	1.5	0.8	2	78	29	9.8	17.4	90	37	5	14
205	0.4	0.9	7	0.3	0.2	2.2	4	65	52	17.4	28.4	90	44	6	17
108	1.9	2.4	34	1.6	2.1	2.1	4	78	32	9.6	18.1	90	43	6	17
110	1.4	1.8	35	1.3	1.6	2.3	4	75	30	13.5	12.8	90	47	6	19
111	1.5	2.2	32	2.7	1.6	1.5	3	80	17	14.7	13.4	92	38	7	19
107	1.7	2.6	44	2.8	2.6	2.7	5	71	45	14.3	18.4	90	50	6	19
112	1.9	2.4	37	1.6	1.6	1.9	4	74	25	10.8	6.9	90	45	6	19
106	0.8	1.1	15	1.1	0.9	1.9	4	81	25	8.8	19.1	91	47	7	20
118	1.3	1.8	22	1.3	1.2	2.5	5	76	23	10.8	6.9	91	45	7	21
211	1.5	2.2	31	2.2	1.4	2.9	6	80	19	14.7	16.0	91	40	8	21
114	1.5	2.1	36	1.8	1.8	2.3	4	78	22	14.0	11.6	91	65	7	23
103	2.0	2.9	26	2.0	1.1	2.3	4	83	22	11.7	11.7	96	34	13	23
429	1.6	2.1	33	2.1	1.9	2.4	4	72	18	11.0	17.6	91	92	7	24
[3]124	2.8	2.8	31	1.4	1.4	2.6	5	82	14	10.9	10.9	93	68	9	24
426	1.5	2.2	20	1.5	1.2	2.8	6	72	22	17.6	14.0	92	70	9	25
[3]430	3.0	3.0	20	1.6	1.5	2.4	4	72	22	6.6	12.3	93	70	9	25
[3]432	3.6	3.6	68	3.2	2.8	2.4	4	76	26	15.6	11.9	91	99	7	25
[3]433	3.6	3.6	47	3.4	3.4	2.2	4	72	16	9.3	7.9	92	92	8	26
428	1.4	2.1	29	1.5	1.2	2.1	4	78	26	14.3	10.2	92	99	8	27
113	1.4	1.9	44	2.1	1.7	2.0	4	78	21	14.0	11.6	93	65	9	27
105	2.1	2.9	26	2.1	2.2	2.2	4	78	22	9.2	10.4	94	76	10	28
121	1.8	2.5	20	2.1	1.8	2.4	4	81	16	12.7	11.0	94	82	10	29
427	1.4	2.0	24	1.6	1.1	2.5	5	74	16	9.1	9.9	93	96	9	30
[3]431	3.8	3.8	67	2.6	1.9	2.7	6	74	18	9.1	16.8	92	96	9	30
[3]120	3.2	3.2	21	2.4	2.5	2.3	4	82	15	10.3	9.8	95	82	12	33
122	1.9	2.5	34	2.2	2.1	3.2	6	74	14	7.1	8.5	95	72	14	34
[3]123	3.9	3.9	37	2.6	2.6	3.3	8	73	14	7.1	8.5	94	72	14	34
[3]119	6.5	6.5	125	6.0	6.2	2.8	6	79	21	8.8	13.5	95	76	14	35

[1] Plots numbered in 100's are Dry Pine South, in 200's are Fresh Pine, and in 400's are Dry Pine North.
[2] Open winds derived from stand winds for danger index calculation from relationships in Cooper (1965).
[3] Asterisks indicate strip head fire ignition.

Table 19.—*Fuel consumption and fire impact (from Lawson 1973)*

Plot[1] number	Initial organic layer depth	Initial organic layer weight	Initial debris weight, 0–0.5 inch diameter	Initial debris weight, > 0.5 inch diameter	Total initial debris weight	Total[2] initial fuel weight	Organic layer consumption depth	Organic layer consumption weight	Debris consumption 0–0.5 inch diameter
	Inches			*Lb/ft²*			*Inches*	*Lb/ft²*	
109	1.4	0.332	0.008	0.015	0.023	0.363	0.35	0.059	0.007
205	1.8	.452	.006	.083	.089	.547	.30	.050	.002
108	1.6	.390	.008	.259	.267	.665	.42	.071	.007
110	1.4	.332	.005	.263	.268	.608	.57	.096	.004
111	1.2	.298	.006	.017	.023	.329	.44	.074	.006
107	1.6	.390	.011	.056	.067	.465	.60	.101	.010
112	1.5	.373	.009	0	.009	.390	.55	.092	.009
106	1.8	.473	.012	.092	.104	.585	.33	.055	.012
118	1.5	.373	.009	.002	.011	.392	.40	.068	.009
211	1.1	.242	.007	0	.007	.255	.52	.087	.007
114	1.3	.315	.007	0	.007	.330	.65	.109	.006
103	1.2	.298	.007	.032	.039	.313	.30	.050	.007
429	1.1	.257	.004	0	.004	.271	.51	.086	.003
124[3]	1.1	.257	.004	.161	.165	.430	.27	.045	.004
426	1.2	.298	.006	.028	.034	.342	.21	.035	.005
430[3]	1.2	.298	.004	0	.004	.312	.20	.034	.004
432[3]	1.4	.332	.007	.437	.444	.786	.37	.062	.007
433[3]	1.0	.241	.005	.001	.006	.257	.47	.079	.004
428	1.3	.315	.005	.002	.007	.330	.50	.084	.005
113	1.7	.432	.006	.356	.362	.802	.54	.091	.006
105	1.1	.257	.004	.004	.008	.273	.30	.050	.003
121	1.2	.298	.007	.009	.016	.322	.21	.035	.007
427	1.3	.315	.003	0	.003	.328	.42	.071	.003
431[3]	1.6	.390	.007	0	.007	.407	.65	.109	.006
120	1.2	.298	.008	.151	.159	.465	.18	.030	.008
122	0.9	.224	.012	.392	.404	.636	.24	.040	.011
123[3]	0.9	.224	.005	.004	.009	.241	.30	.050	.005
119[3]	1.1	.257	.012	.358	.370	.635	.35	.059	.012

[1] Plots numbered in 100's are Dry Pine South, in 200's are Fresh Pine, and in 400's are Dry Pine North.
[2] Includes herbaceous fuel loading and consumption of 0.008, 0.006, and 0.010 lb/ft² for Sites 1, 2, and 4, respectively.
[3] Strip head fire ignition.

hemlock slash on the Olympic Peninsula. They used the same planar intersect transects before and after burning. They also tagged all pieces greater than 3 inches in diameter so they could measure diameter loss from burning. They indicate the following fuel consumption:

Status	Fine fuels 0–3 inch diameter	Coarse fuels Sound 3 inch +	Coarse fuels Rotten 3 inch +	Total down and dead fuels	Average duff depth	Average fuel depth
		Tons/acre			*Inches*	
Before burning	15.54	18.90	12.74	47.18	2.35	8.6
After burning	5.50	13.94	9.42	28.86	1.10	0.7
Volume consumed	10.04	4.96	3.32	18.32	1.25	7.9
Percent consumed	65	26	26	39	53	92

They indicate 18.3 tons per acre, or 39 percent of the down and dead fuels, were consumed.

Muraro (1975) measured slash and duff reduction under a variety of conditions representing most operational burns in cedar-hemlock logging slash. Most burns consumed 75 to 98 percent of slash less than 3 inches in diameter and 35 to 60 percent of material over 10 inches in diameter. The sharp drop in fuel consumption occurred between 3 and 10 inches in diameter. Duff consumption ranged from 45 to 60 percent depending on the duff moisture content under which the burning was conducted.

Table 19.—*(continued)*

Plot[1] number	Debris consumption, > 0.5 inch diameter	Total debris consumption	Total[2] fuel consumption	Fuel[2] consumed by heading front	Mean scorch height	No. of candling trees	Mature tree mortality to Oct. 1972	Advance regeneration mortality to Oct. 1972
		Lb/ft²			*Feet*		*Percent*	
109	0	0.007	0.074	0.074	0.8	0	15	97.5
205	0	.002	.058	.058	0	0	0	0
108	.044	.051	.130	.099	.6	1	11	100
110	.092	.096	.200	.138	1.7	0	6	100
111	.017	.023	.105	.101	2.4	4	20	99.4
107	.018	.028	.137	.121	1.3	1	5	97.5
112	0	.009	.109	.109	2.7	3	33	100
106	.092	.104	.167	.098	1.2	1	0	100
118	.002	.011	.087	.086	6.3	10	54	100
211	0	.007	.100	.100	3.1	4	45	100
114	0	.006	.123	.123	6.9	6	73	100
103	0	.007	.065	.065	1.5	1	32	100
429	0	.003	.099	.099	1.6	2	16	100
124[3]	.060	.064	.117	.078	2.6	1	38	100
426	.024	.029	.072	.063	1.4	0	14	99.3
430[3]	0	.004	.046	.046	4.5	2	31	97.0
432[3]	.166	.173	.245	.134	5.2	1	71	99.4
433[3]	0	.004	.093	.093	4.8	5	54	100
428	0	.005	.099	.099	1.4	1	40	98.0
113	.184	.190	.289	.162	5.3	7	29	100
105	.002	.005	.063	.063	1.3	3	20	100
121	.006	.013	.056	.055	2.5	4	57	100
427	0	.003	.084	.084	1.9	2	15	100
431[3]	0	.006	.125	.125	2.7	2	17	98.3
120[3]	0	.008	.046	.046	3.3	4	64	100
122	.104	.115	.163	.095	1.8	1	4	100
123[3]	.004	.009	.067	.067	2.9	1	25	100
119[3]	.182	.194	.261	.137	5.9	2	83	100

[1] Plots numbered in 100's are Dry Pine South, in 200's are Fresh Pine, and in 400's are Dry Pine North.
[2] Includes herbaceous fuel loading and consumption of 0.008, 0.006, and 0.010 lb/ft² for Sites 1, 2, and 4, respectively.
[3] Strip head fire ignition.

Douglas-fir

Fuel consumed in a Douglas-fir slash burn were reported by Fritschen et al. (1970). The 18.4-acre prescribed burn was conducted on Pack Forest near Mount Rainier. Fuel weights before and after burning were:

Fuel class	Moisture content before burn	Fuel load: Before	Fuel load: Reduction
	Percent	*Tons/acre*	
Duff	19–48	9.87	5.04
0.394–inch diameter	17–25	[1]3.66	[1]3.84
0.394 to 3.94 inch diameter	19–23	5.98	1.21
3.94 inch diameter		19.9	5.49

[1] Data as given, probably due to sampling error.

The fire was ignited about 1:30 p.m. on June 25 using jellied gasoline and electrical ignition. Temperature varied from 78° to 86° F, relative humidity from 46 to 56 percent, and wind from 1.3 to 17 feet per second.

Swanson (1974, 1976) measured forest floor fuel reduction by prescribed burning in a young Douglas-fir stand in western Washington.

Average reductions were as follows:

Fuel	Fuel load: Before	Fuel load: After	Percent reduction
	(Tons/acre)		
1 hr. T.L.	1.6	0.2	82
10 hr. T.L.	2.3	0.9	67
100 hr. T.L.	5.0	3.2	41
> 100 hr. T.L.	36.0	22.7	31
Duff	39.6	13.7	71

Conditions for burning were as given below:

	Slash site (next to slash)	Wet site	View point	View point (unsuccessful)
Air temperature	74°–76° F	71°–74° F	60°–58° F	70° F
Relative humidity	56–53%	58–50%	55–90 + %	60%
Wind	2 mi/h	slight breeze	1 mi/h	2–4 mi/h
Fuel moisture				
0.00–0.25	17%	22%	12%	22%
0.26–0.99	16%	21%	13%	22%
needles	20%	28%	15%	46%
humus	49%	59%	—	44%
Days since rain	10	14	5	3
Amount of rain	.12 in.	trace	trace	.10 in.
Time of day	p.m.	a.m.-p.m.	p.m.	p.m.

Of the burns, conditions for burning at the wet site and the unsuccessful attempt at the view site could be considered unsatisfactory. The wet site burn eventually consumed large jackpots of fuel, but did not spread through most of the plot. The conditions for both burns give insight to the wetter limits of prescribed burning in Douglas-fir.

Capell (1976) did a follow-up study on the prescribed burning results reported by Swanson (1974, 1976). His measurements conducted in 1975, 2 years after burning, indicate that surface fuel loads in the 0.0 to 0.25 inch size class range from 20 to 50 percent of preburn levels. Increase from immediate postburn loads was 0.2 to 0.5 tons per acre. The 0.26 to 1.00 inch size class fuels increased up to 0.7 tons per acre and the 1 to 3 inch class up to 1.0 tons per acre over the immediate postburn fuel loads. Dead and down fuel loads from the > 3 inch class was variable, often coming from standing dead stems burned off at the base during the fires. Duff fuel loads were from 3 to 42 percent preburn fuel loads and showed only a slight increase in the 2 years following burning.

Ward (1977) reported fuel consumption from two prescribed burns in west coast Douglas-fir stands in the Oregon Cascades as follows:

	Diameter class	1972 Preburn	1972 Postburn	1976 After logging
		Tons/acre		
Area 1	0–3	10.3	0.3	16.1
	3+	37.8	11.8	8.2
Total		48.1	12.1	24.3
Area 2	0–3	8.5	3.5	7.9
	3+	65.8	14.9	71.3
Total		74.3	18.4	79.2

The prescription called for winds of 0 to 7 miles per hour, relative humidity of 35 to 70 percent, and fuel moisture of 12 to 22 percent. Flames averaged 3 feet in length in the first unit and 2 feet in the second. Live understory vegetation was reduced considerably after the fire, but not recorded in terms of amount of fuel consumed.

Interior Ponderosa Pine

Gordon (1967) reported fuel reduction by well-documented prescribed burns in young ponderosa pine stands in northern California. He found litter fuels were reduced, on the average, from about 18 tons per acre to 4 tons per acre on 11 plots burned twice, 1 year apart. By 3 years after the first burn, litter fuels had returned to about 8 tons per acre. On nine plots burned once, 12 tons of litter fuel per acre were reduced to 2 to 3 tons per acre immediately, but had risen to about 7 tons per acre by the third year. Down and dead fuels 1 to 4 inches in diameter were reduced from 2 to 4 tons per acre by one or two burns to 1 to 2 tons per acre, but by the end of 3 years had risen to 13 to 16 tons per acre, primarily from small trees, shrubs, and branches killed by the fire. Fuels over 4 inches in diameter were reduced from 25 to 13 tons per acre immediately after the first burn to 6 tons per acre after the second burn. By 3 years after the first burn the large fuel had risen to about 10 tons per acre. In plots burned once, down and dead materials over 4 inches in diameter were reduced from about 4 tons per acre to less than 2 tons per acre, and rose only about 1 ton per acre in the years following the burn. He presents no figures on variation in fuels, but does mention the burns were spotty, which would yield wide variation in consumption.

The Forest Residue Program of the PNW Station monitored prescribed burning in ponderosa pine-bitterbrush-manzanita (*Arctostaphylos patula*) types on the Deschutes National Forest. Average consumption, 3 weeks apart, changed from 68 to 32 percent (table 20).[16] Burning conditions for the two areas were very similar:

	Burn of 5/2/74 (4 acres)	Burn of 5/23/74 (15 acres)
Relative humidity, percent	38–51	29–51
Wind, miles per hour	3–10	2–4
Fuel stick moisture, percent	10–11.5	8

Table 20.—*Fuel load reductions as measured by the Forest Residues Program on two prescribed burns on the Deschutes Natinal Forest*

Fuel size class	Fuel loads		
	Preburn	Postburn	Reduction
Inches	*Tons/acre*		*Percent*
Burn of 5/2/74			
0–¼	0.1	0.03	71
¼–1	1.6	0.4	74
1–3	1.8	0.7	60
3+	16.7	5.4	68
Total	20.2	6.5	68
Burn of 5/23/74			
0–¼	0.04	—	100.0
¼–1	0.41	0.25	39.9
1–3	2.03	0.87	57.1
3+	65.54	45.29	30.9
Total	68.02	55.36	31.8

Fuel loads measured in a study on effects of fire on nutrients in central Oregon ponderosa pine stands (Wallace 1976) were as follows:

Fuel	Fuel load range (Tons/acre)
1 hr. T.L.	0.03– 0.2
10 hr. T.L.	0.2 – 0.7
100 hr. T.L.	0.1 – 2.5
100 hr. T.L.	0.09– 1.0
Duff	5.2 –11.7
Total	9.4 –14.4

[16] Ward, Franklin R. Personal communication. Data on file at Forest Residues Program, Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Extensive shrub cover by several shrub species, including snowbrush ceanothus, greenleaf manzanita, and chinkapin (*Castanopsis chrysophylla*), was measured but not converted to fuel quantities.

Martin[17] presented data on ponderosa pine thinning slash fuel loads and consumption in 10 different prescribed burns of 0.12 to 57 acres in size. Burning conditions were as follows:

Time:	Autumn and spring
Temperatures:	43 °–68 ° F
Relative humidity:	30–60 percent
Wind in stand:	0.6–8 mi/h
Firing pattern:	Back fire and strip head fire
Flame lengths:	0.7–11 feet
Fuel moistures:	
1 hr. T.L.	7–14 percent
10 hr. T.L.	10–50 percent
100 hr. T.L.	10–70 percent
100 hr. T.L.	10–110 percent

The prescription conditions were designed to consume most of the smaller fuels to reduce fire hazard while leaving most of the larger fuels to prevent large heat outputs. Fuels ranged from red slash (with needles on) under trees as small as 11 feet tall to 8-year-old gray slash (without needles) under stands up to 39 feet tall. Apparently less than 1 percent of the save trees on any area will die. Dead and down fuels were measured by planar intersect before and after burning (Brown 1971, 1974), with the following fuel consumption on the 10 areas.

	Percent fuel consumption on 10 areas		
	Average	Standard deviation	Standard error
Foliage	96.0	1.22	0.5–5
1 hr. T.L.	55.0	46.90	14.8
10 hr. T.L.	55.0	26.60	8.4
100 hr. T.L.	15.9	30.80	9.8
>100 hr. T.L.	44.0	38.70	12.2
Duff	61.0	26.50	8.4

Prescribed burning two areas of 100 and 300 acres in ponderosa pine-bitterbrush-curlleaf mountain-mahogany (*Cercocarpus ledifolius*) at Lava Beds National Monument in extreme northern California reduced some dead and down fuels but increased others (tables 21 and 22).[18]

[17] Martin, R. E. 1978. Principles and prescriptions for burning ponderosa pine thinning slash. Paper presented at the AAAS–SAF Meeting, Seattle, Wash., June 1978.

[18] Data on file at the USDA Forest Service Silviculture Laboratory, Bend, Oreg.

Table 21.—*Dead and down fuels before and after burning, Caldwell Butte Burn, May 1977, 247 acres*

Fuel size class	Fuel load		
	Before	After	Reduction
Inches		*Tons/acre*	
0–.25	0.301	0.264	0.037
0.25–1	0.665	0.442	[1]0.223
1–3	0.750	0.723	0.027
3+	0.0	0.357	− 0.357
Duff	1.80	1.93	− 0.19

[1] Reduction significant at 95 percent level of confidence.

Table 22.—*Dead and down fuels before and after burning, Headquarters Burn, July 1977, 296 acres*

Fuel size class	Fuel load		
	Before	After	Reduction
Inches		*Tons/acre*	
0–.25	0.121	0.217	− 0.096
0.25–1.0	0.516	0.304	0.212
1–3	1.12	0.936	0.184
3+	26.70	0.661	[1]26.00
Duff	4.30	2.680	[1]1.62

[1] Reduction significant at 99 percent level of confidence.

The data very interestingly show an increase in some dead and down fuels after burning. Since the same lines were sampled before and after burning, most of the increase can be attributed to shrubs, mostly bitterbrush and mountain-mahogany, burning off at the base and falling. The large amount of 3+ inch size of fuel on the Headquarters Burn came from decadent mountain-mahogany and ponderosa pine logs killed by the western pine beetle (*Dendroctonus brevicomis*) in the late 1920's and early 1930's.

The total fuel consumed will be quite a bit greater than indicated in the two tables, but data on consumption of shrubs and herbaceous materials have not yet been analyzed.

Research Needs

Some data are available on fuels and the effects of fire on fuels for the Pacific Coast States. Alaska and Hawaii have the least data, whereas southern California has the only dynamic fuel model in chaparral. The bits and pieces of fuels information available in other parts of the Pacific Coast need to be built into dynamic fuel models to help the land manager predict hazard. By incorporating information from timber and biomass studies, dynamic models for some types such as sage-grass and ponderosa pine could probably be developed within a year. A great deal more data will be needed on the effects of fire on some fuel components, especially shrubs and trees. There is a need to link the fuels research in with research on timber and other resources to insure the most useful and integrated dynamic fuel models.

SUMMARY OF FUELS KNOWLEDGE AND KNOWLEDGE GAPS

Generally, our knowledge of fuels is sufficient enough so that stylized models as represented by those in the National Fire Danger Rating System (Deeming et al. 1978) and Albini (1976) are adequate for general fire management planning. Other, more local stylized models are being developed in given areas. In most cases we lack a calibration of stylized fuel models for local situations. We must develop knowledge of variations in fuels and resultant fire behavior as it fits local and site-specific situations.

Static fuel models, which predict fuel load at a given stand condition, are available for many fuels in different parts of the country. However, these data represent only a given stage of fuel progression in a vegetation type and generally not enough data are available to develop even a close approximation of fuel progression over time, the dynamic model.

Dynamic fuel models are available only for limited fuel situations. Notable dynamic fuel models are those for chamise chaparral in southern California and for the pine-palmetto-gallberry types of the Southern Coastal Plain.

A brief summary of knowledge and knowledge gaps:

Area of country	*Fuel models available and appropriate*
South and Southeast	
1. Stylized	All types: yes
2. Static	Natural and activity fuels: some on pine but not on hardwoods

Area of country	*Fuel models available and appropriate*
3. Dynamic	Pine-palmetto-gallberry: 25 year model; essentially nothing on hardwoods
North Central and Northeast	
1. Stylized	Activity fuels: yes
2. Static	Activity fuels: yes
3. Dynamic	"Minnesota mix": 5 year; nothing on northern hardwoods
Pacific Southwest	
1. Stylized	Yes
2. Static	Bits and pieces
3. Dynamic	Chamise: 50 years Others: 2–3 years Grass-range data could be interpreted
Rocky Mountains	
1. Stylized	All types: yes
2. Static	Pine: pieces Shrubs: pieces Spruce-fir: not that important
3. Dynamic	None
Intermountain	
1. Stylized	Range: yes Activity fuels: yes Natural: yes
2. Static	Activity fuels: yes Larch-fir: some
3. Dynamic	Activity: 5 year Range data could be interpreted
Alaska	
1. Stylized	Interior: does not work
2. Static	Black spruce: bits and pieces
3. Dynamic	Black spruce: 25 years (data must be interpreted for fuels parameters)
Hawaii	
1. Stylized	Work fairly well
2. Static	Some biological data but must be interpreted
3. Dynamic	Some biological data but must be interpreted
Pacific Northwest	
1. Stylized	Natural and activity fuels—mostly work well
2. Static	Activity and natural: bits and pieces
3. Dynamic	Activity: 5 years Natural: range data to be interpreted Pine-shrub and shrub-grass: some models in 2 years

List of knowledge and knowledge gaps:

A. Stylized models do a reasonable job of representing most fuel complexes; some exceptions may exist.
B. There is a lack of adaptation or calibration of stylized fuel models to fit localized fuel situations.
C. Fragmented data representing case histories exist for many fuel situations. Data are generally lacking in a useful fuel description context, but many data in biomoss studies could be interpreted by subsampling to develop useful fuel data.
D. Dynamic fuel models that represent fuel changes with time or with biotic and abiotic factors exist only for very limited, although important, fuels situations.
E. Knowledge of fuels as related to any systematized description of vegetation is very limited; systematized descriptions of vegetation are often missing.
F. Effects of fire on fuels, especially long-range effects, represent a large gap in knowledge. Data and models of the effects of fire on fuels under varying fuel and weather conditions are especially needed.

RESEARCH PRIORITIES

Some priorities can be assigned to general research needs in fuels. The priorities are based on trying to get the most useful information to managers as soon as possible, and improving on the information and developing more sophisticated models later.

General priorities are:

1) Develop procedures to calibrate stylized models to local situations.

   Stylized models are those with given fuel parameters (National Fire Danger Rating System (Deeming et al. 1978) and Albini (1976)). The stylized models would be compared with local fuel situations particularly in terms of fire behavior under given weather conditions.

2) Locate and interpret appropriate biomass literature.

   Biomass literature may be very useful in developing dynamic fuel models for various habitat types. Since data collected in biomass studies may differ from needs to evaluate fuels, additional subsampling studies may be needed to develop the proper fuel parameters.

3) Develop procedures to apply stylized fuel models to successional situations.

   By developing these procedures we could give managers the tools to help fit stylized fuel models to given stages of ecological succession. The procedure would help the manager make decisions on what fuel model to use and how to decide when to switch to a more appropriate model.

4) Use successional models to develop dynamic fuel models, including fuel consumption.

   Working with developed successional models or with researchers developing such models, the goal would be to develop dynamic fuel models for various habitat types. The dynamic fuel model should include input on stand conditions, site, disturbances, and decomposition. The effects of fire on fuels under different conditions should be a part of the fuel model.

Another problem, although not specifically a part of fuels research, is the need for a uniform vegetation classification system. The various systems presently being used make dynamic fuel modeling less unified and much more difficult.

CONVERSION FACTORS

To Convert	*To*	*Multiply By*
Acres	Hectares	0.4047
Btu	Kilojoules	1.055
Calories	Joules	4.186
Calories	Kilojoules	0.004186
Centimeters	Inches	0.3937
Cubic feet	Cubic meters	0.02832
Cubic feet/acre	Cubic meters/hectare	0.06998
Cubic meters	Cubic feet	35.31
Cubic meters/hectare	Cubic feet/acre	14.29
Feet	Meters	0.3048
Grams/square centimeter	Kilograms/square meter	10.0
Grams/square meter	Kilograms/square meter	0.001
Hectares	Acres	2.471
Inches	Centimeters	2.540
Joules	Calories	0.2389
Kilograms	Pounds	2.205
Kilograms/square meter	Grams/square centimeter	0.1
Kilograms/square meter	Pounds/square foot	0.2048
Kilograms/square meter	Tonnes/hectare	10.0
Kilograms/square meter	Tons/acre	4.461
Kilojoules	Btu	0.9480
Kilojoules	Calories	238.9
Meters	Feet	3.281
Pounds	Kilograms	0.4535
Pounds/square foot	Kilograms/square meter	4.883
Pounds/square foot	Tons/acre	21.78
Tonnes	Tons	1.023
Tonnes/hectare	Kilograms/square meter	0.1
Tonnes/hectare	Pounds/square foot	0.02048
Tonnes/hectare	Tons/acre	0.4460
Tons	Tonnes	1.102
Tons/acre	Kilograms/square meter	0.2243
Tons/acre	Pounds/square foot	0.04591
Tons/acre	Tonnes/hectare	2.242

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*U.S. GOVERNMENT PRINTING OFFICE : 1982 O-368-292/656